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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 555

Guidance and Control for Future Air-Defence Systems

(Techniques de guidage/pilotage pour les systèmes futurs de défence anti-aérienne)

Papers presented at the Mission Systems Panel 1st Symposium held in Copenhagen, Denmark from 17th May to 20th May 1994.

NORTH ATLANTIC TREATY ORGANIZATION

Published January 1995

Distribution and Availability on Back Cover

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

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Published January 1995

ISBN 92-836-0008-8

Printed by Canada Communication Group
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Theme

Advanced air-defence has become one of the primary issues of operational concern for NATO. Within this context operational aspects of potential scenarios must be expected to be considerably diversified. Previously assumed scenarios have become obsolete and NATO must redefine the structure and role of its air-defence.

Advances in guidance and control techniques and technologies which can be applied to battle management, threat detection and identification as well as threat deception and suppression are of great importance (technology push).

The Gulf War has demonstrated how stealth technology can reduce the effectiveness of air-defence systems. Advances in stealthy and fast moving nap-of-the-earth strategic and tactical weapon systems as well as strategic and tactical ballistic missiles, operating either individually or in combination necessitates the development and application of effective guidance and control techniques (requirements pull) for advanced air-defence.

The topics covered by the Symposium will include:

— Air Defence Architecture Study and Ballistic Missile Defence

— Advanced Sensor Technology and Techniques

— Data Fusion, Tracking and Identification

— Threat Detection, Suppression and Situation Assessment

— Missile Guidance and Control

— Future Air Defence Aircraft

— C^3I aspects

Thème

La défense anti-aérienne de pointe est l'une des premières préoccupations opérationnelles de l'OTAN. Dans ce contexte, il faut s'attendre à ce que les aspects opérationnels des scénarios possibles soient considérablement diversifiés. Les scénarios établis antérieurement sont devenus obsolètes et l'OTAN doit redéfinir le rôle et la structure de sa défense anti-aérienne.

Les progrès réalisés dans les techniques et les technologies de guidage et de pilotage qui sont susceptibles d'être appliquées à la gestion de la bataille, la détection et l'identification de la menace, ainsi qu'à la déception et la suppression de la menace sont d'une grande importance (la poussée des technologies).

La guerre du golfe a montré comment les technologies de furtivité peuvent réduire l'efficacité des systèmes de défense anti-aérienne. Les progrès réalisés dans le domaine de la furtivité des systèmes d'armes tactiques et stratégiques utilisant des engins furtifs évoluant à grande vitesse et en rase-mottes, ainsi que des missiles balistiques tactiques et stratégiques, opérant soit seuls soit en formation, nécessitent le développement et l'application de techniques efficaces de guidage et de pilotage pour la défense anti-aérienne de pointe (appel de technologies).

Les sujets examinés lors du symposium comprennent:

— Étude de la configuration de la défense anti-aérienne et de la défense anti-missiles balistiques,

— Progrès réalisés dans le domaine des technologies et techniques des capteurs,

— Fusion de données, poursuite et identification,

— Détection, suppression et évaluation de la menace,

— Guidage et pilotage des missiles,

— Futurs appareils de défense aérienne,

— Aspects C^3I.

Mission Systems Panel Officers

Acting Chairman: Mr. J K RAMAGE
Chief, Flight Control
Flight Dynamics Directory
WL/FIGS, Bldg 146
2210 Eighth St, Ste 11
Wright-Patterson AFB, OH
45433-7521
United States

Technical Programme Committee

• Chairman:	Dr D F LIANG	CA
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	Dr Ing B MAZZETTI	IT
	Ir G J ALDERS	NE
	Mr J BARDAL	NO
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	Mr G F BUTLER	UK
	Mr S BUTLER	UK

Panel Executive

From Europe:

Lt-Col P FORTABAT
Executive, MSP
AGARD-OTAN
7 Rue Ancelle
F-92200 Neuilly-sur-Seine, France

For USA and Canada only:

AGARD-NATO
Attention: MSP Executive
PSC 116
APO AE 09777

Telephone: 33 (1) 4738 5780/82 — Telex: 610 176F — Fax: 33 (1) 4738 5799/6720

Host Nation Coordinator

Mr E DANNENBERG
Danish Defense Research Establishment
PO Box 2715
DK-2100 Copenhagen 02
Denmark

Acknowledgements/Remerciements

The Panel wishes to express its thanks to the Danish National Delegates to AGARD for the invitation to hold this meeting in Copenhagen and for the facilities and personnel which made the meeting possible.

Le Panel tient à remercier les Délégués Nationaux du Danemark près l'AGARD de leur invitation à tenir cette réunion à Copenhague et de la mise à disposition de personnel et des installations nécessaires.

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* Published in classified volume CP-555 (Supplement).
! Not available at time of printing.

SESSION III — ACQUISITION, POINTING AND FIRE CONTROL AND SYSTEM INTEGRATION
Chairman: Dr B. Mazzetti (IT)

SESSION IV — DATA FUSION, TRACKING AND IDENTIFICATION
Chairman: Mr. G.F. Butler (UK)

* Published in classified volume CP-555 (Supplement).
! Not available at time of printing.

TECHNICAL EVALUATION REPORT
on the
MISSION SYSTEMS PANEL
1st Symposium
on
GUIDANCE AND CONTROL TECHNIQUES FOR FUTURE AIR-DEFENCE SYSTEMS

by

Paul Zarchan
Charles Stark Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA, USA

EXECUTIVE SUMMARY

The 1st Symposium of the AGARD Mission Systems Panel (MSP) was convened in Copenhagen, Denmark, 17-20 May 1994. The Symposium dealt with various guidance and control techniques for future air-defence systems. The program, as presented in the Symposium, is appended to this report. The overall theme is described in the following paragraphs.

Advanced air-defence has become one of the primary issues of operational concern for NATO. Within this context operational aspects of potential scenarios must be expected to be considerably diversified. Previously assumed scenarios have become obsolete and NATO must redefine the structure and role of its air-defence.

Advances in guidance and control techniques and technologies which can be applied to battle management, threat detection and identification as well as threat deception and suppression are of great importance (technology push).

The Gulf War has demonstrated how stealth technology can reduce the effectiveness of air-defence systems. Advances in stealthy and fast moving nap-of-the-earth strategic and tactical weapon systems as well as strategic and tactical ballistic missiles, operating either individually or in combination, necessitates the development and application of effective guidance and control techniques (requirements pull) for advanced air-defence.

The keynote address discussed the importance of the hit-to-kill concept in yielding the required lethality against various theater missile defence threats and how hit-to-kill has been made possible through advances in guidance and control technology. The invited papers also discussed the importance of theater missile defence and identified key technology areas for future work. Session 1 was concerned with both the architectural issues and the guidance and control requirements for theater missile defence systems. Various simulation tools for evaluating system performance were also discussed. Session 2 information concerning advanced sensor suites used for future air defence systems. In addition, technical papers were presented on detector technology and new definitions for the figure of merit. Session 3 showed how acquisition, tracking and pointing are important for the boost-phase intercept problem. In addition, information on the status of various experiments was presented. Session 4 was concerned with data fusion as applied to missile guidance algorithms and the combining of informationfrom sensors observing air-breathing threats. The use of artificial intelligence and improving the man-machine interface were presented as valid technologies for the multi-sensor data fusion problem. Session 5 discussed the application of visual stereoscopy for inverse synthetic aperture radar and using RF emissions for detection, localization and identification. Session 6 presented both theory and practice for missile guidance and control. Session 7 showed how fuzzy logic could be applied to the C^3I problem. Finally, the Round-Table Discussion was rather lively and the points raised were excellent. It is too bad that some of the questions/concerns were not raised after the appropriate technical presentations.

Thirty-two presentations were made at this Symposium. Most of the papers on ballistic missile defence did not get into the technical details of the challenges in this area. Perhaps this was due to classification problems or for fear of giving away trade secrets. On the other hand most of the papers on data fusion, tracking and identification went into significant detail. I would recommend that the Mission Systems Panel consider a Symposium exclusively devoted to Theater Missile Defence.

Not withstanding minor disappointments, the Symposium achieved most of its objectives in bringing together in a timely fashion, many of the leading engineers in the guidance and control field. Both the Program Committee, National Hosts and Panel Executive/Secretary should be congratulated for their outstanding efforts in arranging the Symposium.

INTRODUCTION

The 1st Symposium of the MSP was titled "Guidance and Control Techniques for Future Air-Defence Systems." The Acting MSP Chairman was Mr. J. K. Ramage (US). The Program Committee chaired by Dr. D. F. Liang (CA) also included

IPA A. Salomon	(FR)
Mr. U. K. Krogmann	(GE)
Dr. Ing. B. Mazzetti	(IT)
Mr. J. Bardal	(NO)
Dr. P. Sanz-Aranguez	(SP)
Mr. G. F. Butler	(UK)
Dr. S. Butler	(US)

Opening remarks concerning the downsizing of various panels were made by Mr. Ramage. Dr. Liang also made a few open remarks about the political and psychological significance of the Scud type tactical ballistic missiles. We were welcomed by our Danish hosts.

The keynote address was presented by Dr. J. David Martin, Director for Strategic Relations, Ballistic Missile Defense Organization, U.S. His talk described the emerging ballistic missile threat and how the U.S. Ballistic Missile Defense Program is responding to that threat. He discussed the importance of the hit-to-kill concept in yielding the required lethality against chemical and biological submunitions and how hit-to-kill has been made possible through advances in guidance and control technology.

Although a key tenet in the U.S. theater missile defense program is to normally develop capability in an evolutionary manner, the U.S. is embarked on an aggressive program to put "rubber on the ramp" as soon as possible so that when the next crisis arrives, the U.S. and it's allies will be better protected than was the case during Desert Storm. There is a plan to coordinate the implementation of theater missile defense programs with friends and allies in order to avoid duplication, reduce costs (or at least to share costs) and to increase interoperability. Dr. Martin concluded by emphasizing that we must work together to meet the threat both technically and economically.

INVITED PAPERS

The first talk, not based on a written paper, was entitled "Ballistic Missile Defense in the Post Cold War Era" and was presented by Mr. C. Morton of the Defense Research Agency (UK). He mentioned that there was a need to understand the lethality phenomenon, discrimination techniques and kill assessment. The speaker believed that there was a significant risk from ballistic missiles due to both proliferation and the relative ease to which chemical warheads could be added to Scud-like missiles.

The second talk in this session was based on the invited paper "NIAG Study on Extended Air Defence Post 2000" by P. J. Mantle of Lockheed Missiles and Space Company (US). The presentation covered some of the key findings by NIAG SG-37 during a one year activity exploring the issues and solutions to the general topic of providing Extended Air Defence capability for NATO and it's Out of Area Forces. It was recognized that there was a need for a Multi-Layer Defense system made up of various combinations of space-based assets, aircraft, missiles and other assets. Key technologies grouped under the headings: computers, software, sensors, communications network, electronic devices, materials & processes, energy storage & lethality and propulsion were identified in the paper. Future funding recommendations were made.

TECHNICAL SESSIONS
SESSION 1: BALLISTIC MISSILE DEFENCE ARCHITECTURE AND AIR-DEFENCE SIMULATION

The first paper (Deas and Tanter) dealt with a ballistic missile defence architecture for Europe. The presentation, which was on an overview level, focused on the important ballistic missile threat. The authors believed that the key problems in theater missile defence were in integration of subsystems not in component technology.

The second paper (Roche and Cotillard) concerned itself with the guidance and control requirements for a possible allied ballistic missile defence system. Two types of threats (medium and long range ballistic missiles), three types of interceptors (i.e., upgraded versions of Patriot, exo/endo interceptors with no air breathing threat capability but able to intercept ballistic missiles and pure exo systems), and three types of architectures (medium range attack, long range rustic attack and long range attack with countermeasures) were discussed in the paper. Some of the key technical issues such as the large deceleration of an endoatmospheric RV making it a difficult target to hit were highlighted and three generic defence architectures were overviewed. Examples of expected footprints were also presented.

The third presentation (Gregoire, Eatock and Richard) concerned itself with the surveillance performance of a space-based radar system. This technical presentation contained numerous tradeoff curves concerning performance and was the first presentation to actually generate questions from the audience.

The next paper (Tanter and Deas) described the simulation SOSIE which is used to evaluate performance against scenarios involving ballistic missile attack. An overview of two other useful simulations (TACSIT and SPOOK) was provided

showing how they could be used in conjunction with SOSIE to yield more insight into the analysis.

The last paper (Seavers and Butler) described an application of the JOUST air combat simulator facility for pilots to model simulated beyond visual range combat. JOUST consists of eight man-in-the-loop pilot stations linked to a powerful computer simulation network. This tool is useful in deciding what makes one fighter aircraft better than another. The authors describe how JOUST combat effectiveness studies focus on aircraft performance, avionic systems and weapon systems. It was mentioned that as a spin-off of JOUST, new tactics have been developed. JOUST is being improved to better model multi-role fighter operations, particularly low level fighter ground attack missions, with digital terrain database within the simulation. The surface-to-air missile representation is planned to be improved together with the detailed modeling of other airborne assets.

SESSION 2: ADVANCED SENSOR TECHNOLOGY AND TECHNIQUES

The first paper (Petersen, Kinashi and Leslie) described the benefits of advanced theater missile defense surveillance provided by the EAGLE airborne sensor suite designed for the AWACS platform. It is shown that precise, early knowledge of threat missile trajectories give defence weapon systems enhanced performance and capability. Using an integrated passive/active sensor suite, EAGLE establishes a very accurate threat track immediately after booster burnout. Early broadcast of precise impact point predictions helps in attack assessment and enables passive defense elements to react sooner. Timely threat launch point estimates aid the counter force response.

The second paper (Phong) discussed the technical details on the fabrication and testing of PB doped BiSrCaCuO detectors. The presentation suggested that these devices might be useful as primary or complimentary detectors in applications which require a wide band coverage in different spectral regions. Since the figure of merit of these devices has not yet been optimized, it is postulated that detector performance can be substantially improved.

The next paper (Uda and Barani) discusses a new figure of merit called the Spreading Factor which helps in evaluating the capability of a detector array in detecting point sources. Using this figure of merit the paper examines some typical detector and system configurations.

The last paper (Coates) discusses the use of IR search and track technology for satisfying the surveillance and threat acquisition sensor requirements for future air-defence systems. Some methods are presented for improving the long range detection and tracking of airborne targets in a ground-based air defense role. Techniques are presented to improve the range performance of passive systems dealing with low observability targets. The use of an IR search and track system in conjunction with a passive millimeter wave sensor is discussed as a way of reducing the adverse effects of weather on an infrared only solution.

SESSION 3: ACQUISITION, POINTING, FIRE CONTROL AND SYSTEM INTEGRATION

The first paper (Humpherys, Wolfe and Gurski) discusses why acquisition, tracking and pointing (ATP) are important for ballistic missile defence - particularly the boost phase intercept problem. The status of various ATP fire control programs such as the ADAPT program and the HABE experiment were discussed in the presentation. The benefits of the ATP assets to theater missile defence are that the platform provides high resolution standoff sensors at low cost and can provide sub microradian tracking and imaging of dynamic targets, active and passive multispectral data and non-cooperative fire control algorithms.

The second paper (Dimiduk, Caylor, Williamson and Larson) gives an overview of the High Altitude Balloon Experiment (HABE) in which a thrusting missile is to be laser tracked and a surrogate laser weapon beam is to be pointed at the target. The acquisition, tracking and pointing system on the High Altitude Balloon Experiment must stabilize and control a relative line of sight between the platform and the target to a 1 microradian accuracy. The SWIR acquisition and MWIR intermediate fine track sensors image the signature of the rocket plume. After hardbody handover, active fine tracking is conducted within a visible focal plane viewing the laser illuminated target body. Since the balloon system is reusable, it is expected to fly many times during the development program.

The third presentation (Avalle and Asperti) discusses an integrated fire and flight control system for future air-defence aircraft.

The fourth paper (Noll, Warm and Kassens) discusses different methods for destroying sensors by using reduced laser energy against the detectors of optical systems (in-band engagement) or using higher laser energy to achieve a thermal destruction of the optics (out-of-band engagement). The environmental and physical phenomena affecting laser weapon performance are examined in the paper. Methods for improving the system's anti-sensor capability are discussed.

The last paper (Watkins, Noonan, Roberts and Upton) discusses a comprehensive program of mission management aid development for the air-defense scenario. A series of workstation prototypes in the areas of sensor management, sensor data fusion, tactical

situation assessment and tactical decision aids are described. The paper examines both the issues involved in the integration process and the benefits to be gained from integration.

SESSION 4: DATA FUSION, TRACKING, AND IDENTIFICATION

The first presentation (Flavell) dealt with the operational benefits of passive sensors for the SHAPE deployable ACCS component.

The second paper (Errington) presents three case studies to illustrate that the design of the estimation and data fusion algorithms play an important role in different parts of the weapon system during different phases of the engagement. Examples are presented showing how multiple model estimators can produce estimates which help bridge the gap between any individual sensor's capability and the target state estimates required for missile guidance. The examples presented in the paper illustrate some important interactions between seekers & sensors, estimation & data fusion and guidance & control. The paper also mentions close interactions with image processing, aerodynamic design, propulsion and the command & control system. The paper concludes that the future design task will require very close liaison between various skill areas to an extent far beyond what has happened in the past.

The third paper (Lyons) summarizes the characteristics of an air tracking algorithm which will be used to upgrade the capability of the North American Aerospace Defense Command and the United States Space Command to track air breathing threats. The paper describes the current system and discusses a candidate correlation system.

The fourth paper (Nahum and Cantalloube) described the design of a multi sensor surveillance system simulation for air defence. The simulation was programmed in C and works on a UNIX platform using X-Windows.

The next presentation (Premji and Ponsford) went into technical detail on multiple target tracking. An overview of track association logic, multiple hypothesis testing, track filters and track fusion was described.

The following technical presentation (Lim, Liang and Blanchette) concerned itself with an air-defense radar surveillance systems tracking assessment. Topics included in the presentation were the nearest neighbor standard filter, the branching algorithm, multiple hypothesis testing and joint probabilistic data association. Numerous test results were presented to demonstrate reliable tracking, easy implementability and system robustness.

The seventh paper (Zuidgeest) demonstrated the potential use of artificial intelligence in the multi-sensor data fusion problem. The goal is to help the operator by processing the huge amount of sensor data and transforming them into concise and surveyable information. The paper shows the potential use of artificial intelligence for representing knowledge and reasoning with it in the context of multi-sensor data fusion.

The eigth paper (Ebmeyer and Freyer) described the AIDEX expert system developed for aircraft identification. The system, using 1000 rules, is programmed in ADA and incorporates data from various sensors and identification sources. The color slides in the presentation demonstrated an excellent man-machine interface. The many questions from the audience indicated that this expert system was indeed unique.

The last paper (Begin, Boily, Mignacca, Shahbazian and Valin) described the demonstration model of a multi-sensor data fusion implementation for the Canadian Patrol Frigate. The paper places emphasis on the architecture of both the simulation and the fusion systems. The implementation discussed in the paper selects simple but proven algorithms which are appropriate for the data available from real sensors installed in the Canadian Patrol Frigate.

Mr. G. F. Butler was innovative as Session Chairman in that he had a standardized question which all presenters had to answer (i.e. What part of this work is science and what part is art?). Even more innovative was the humorous response he received from Dr. Zuidgeest who presented his answer in cartoon form. In general most participants in Mr. Butler's session admitted that their work was approximately 50% science and 50% art.

SESSION 5: THREAT DETECTION, SUPPRESSION AND SITUATION ASSESSMENT

The first paper (Drake, Wallace, apRhys and Humphries) discusses the application of visual stereoscopy for inverse synthetic aperture radar utilizing liquid crystal switching. Experimental results from field testing are discussed and enhancements are demonstrated. Potential applications include ship classification and land target classification.

The second paper (Rose) discusses electronic combat and lethal defence suppression which means destroying radar sites even if they turn off electronically. In this case the RF emissions are only used as an initial means of detection, localization and identification.

The third paper (Swedenburg) discussed several examples of how a red team has been used to devise countermeasures. The paper describes the experience of the U.S. Ballistic Missile Defense Organization Theater Missile Defense Red Team since the 1991 Gulf War and

the value it has provided U.S. missile designers.

SESSION 6: MISSILE GUIDANCE AND CONTROL

The first paper (Meloux and Delpy) describes long range guidance for a homing missile. Details of the mathematics and simulation results can be found in the paper.

The second presentation (Leek and Tilsley) dealt with the guidance and control aspects of ASRAAM. Three unique features of ASRAAM are its low drag for extended range, high angle of attack operation for increased maneuverability and the use of a transputer for increased processing power. The high angle of attack capabilities presented many challenges in the design of a flight control system.

SESSION 7: C^3I ASPECTS

The first paper (Guerchet, Germain, Blanchard and Aubert) shows that to maintain overall performance of the C^3 system inspite of limited communication bandwidth, the principles of data exchange management are required. Fuzzy logic is used in selecting the required data to maintain a tactical air picture of sufficient quality.

The second presentation (Flavell for Retzer) discussed the air command and control system surveillance exploratory prototype. An overview was provided on the surveillance system along with it's architecture. With this system a capability has been developed to support the evaluation of operational and technical options for future air picture generation systems.

ROUND TABLE DISCUSSION

A lively round table discussion followed the papers. In general, the issues which were raised during the ensuing discussion were excellent and its too bad that some of the questions/concerns were not raised after the appropriate technical presentation. Below is a summary of the various points made during the discussion.

- Concern was raised that by building on existing systems for theater missile defence, the Europeans are being left out.
- With the emphasis on acquisition and the pressure to field a theater missile defence system as soon as possible using off-the-shelf technology, less emphasis is being placed on technology development.
- Why is the U.S. relying so heavily on the hit-to-kill concept?
- U.S. Army says hit-to-kill is the way to go to reduce cost and increase lethality.
- There is going to be an emphasis on boost phase intercept because that's where the payoff is greatest.
- NATO can help theater missile defence with component technologies.
- Sensor technology is being driven by detector technology.
- How can we use sensors in a better way.
- Improvements in simulation technology will change the way we design systems.
- Understanding the physics is paramount to solving problems.
- Are there opportunities for bringing ground-based and airborne systems together?
- Is it possible to make a dual usage interceptor?
- How can we protect people from friendly fire?
- We always want to keep a human in the loop because an aircraft (i.e., MIG 29) can be a friend or a foe.
- Precision guidance saves lives.
- Europe can participate in the future but not with current systems.
- We must address all threats (i.e., cruise missiles, aircraft and ballistic missiles)
- Today's systems are not effective against tactical ballistic missiles.
- Endgame guidance and BMC^3 are important.

RECOMMENDATIONS

I would recommend that the Mission Systems Panel consider a Symposium exclusively devoted to Theater Missile Defence.

APPENDIX
FINAL PROGRAM
MISSION SYSTEMS PANEL 1st SYMPOSIUM on GUIDANCE AND CONTROL TECHNIQUES FOR FUTURE AIR-DEFENCE SYSTEMS

Keynote Address: "The Challenge of Defending Against Ballistic Missiles" by Dr. David J. Martin, Deputy for Strategic Relations, BMDO, Washington, DC, US

INVITED PAPERS

<u>Ballistic Missile Defence in the Post Cold War Era</u>

C. Morton	Defence Research Agency, Farnborough, UK

<u>NIAG Study on Extended Air Defence Post 2000 (EAD-2000)</u>

P. J. Mantle	Lockheed Missiles and Space Company, Sunnyvale, CA, US

SESSION 1 - BALLISTIC MISSILE DEFENCE ARCHITECTURE AND AIR DEFENCE SIMULATION
Chairman: Dipl.-Ing. U. K. Krogmann (GE)

SESSION II - ADVANCED SENSOR TECHNOLOGY AND TECHNIQUES
Chairman: Dr. S. Butler (US)

SESSION III - ACQUISITION, POINTING, FIRE CONTROL AND SYSTEM INTEGRATION
Chairman: Dr. B. Mazzetti (IT)

SESSION IV - DATA FUSION, TRACKING, AND IDENTIFICATION
Chairman: Mr. G. F. Butler (UK)

The Operational Benefits of Passive Sensors for the SHAPE Deployable ACCS Component
R. C. Flavell — SHAPE Technical Centre, The Hague, NE

An Integrated Approach to the Tracking and Data Fusion Needs of Guided Weapons
I. Errington — British Aerospace Defence Ltd., Bristol, UK

Air Tracking for Defense of North America
M. Lyons — The MITRE Corporation, Colorado Springs, CO, US

Conception de Systèmes de Surveillance et de Défense Antiaérienne Multi-senseurs
(Design of Multi-Sensor Surveillance Systems for Air Defence)
C. Nahum, H. Cantalloube — ONERA, Chatillon, FR

Multi Sensor Data Fusion for Integrated Maritime Surveillance
A. Premji, A. M. Ponsford — Raytheon Canada Limited, Waterloo, Ontario, CA

Air Defence Radar Surveillance System Tracking Assessment
S. S. Lim — Computing Concepts, Nepean, Ontario, CA
D. F. Liang, M. Blanchette — Defence Research Establishment, Ottawa, Ontario, CA

Multiradar Multiple Target Tracking Based on Constellation Matching and Kalman Filter
A. K. C. Wong — University of Waterloo, Waterloo, Ontario, CA
H. Leung — Defence Research Establishment, Ottawa, Ontario, CA

Multi-Sensor Data Fusion in Command and Control and the Merit of Artificial Intelligence
R. G. Zuidgeest — National Aerospace Laboratory, NLR, Amsterdam, NE

AIDEX: An Expert System for Aircraft Identification
J. Ebmeyer, H. Freyer — Siemens AG, Unterschleischeim, GE

Architecture and Implementation of Multi-Sensor Data Fusion Demonstration Model Within the Real-Time Combat System of the Canadian Patrol Frigate
F. Begin, E. Boily, T. Mignacca, E. Shahbazian, P. Valin — UNISYS GSG Canada, Inc., Montreal, Quebec, CA

SESSION V - THREAT DETECTION, SUPPRESSION AND SITUATION ASSESSMENT
Chairman: Dr. J. Niemela (US)

Stereoscopy of Small Target Radar Imagery
D. Drake, R. J. Wallace — SWL Inc, Vienna, VA, US
T. ApRhys — Naval Reasearch Laboratory, Washington, DC, US
D. Humphries — BMDO, Washington, DC, US

Electronic Combat and Lethal Defense Suppression
L. J. Rose — ASC OL/YHS, Eglin AFB, FL, US

Using a Red Team To Devise Countermeasures
R. L. Swedenburg — USAF, BMDO/DSIM, Washington, DC, US

SESSION VI - MISSILE GUIDANCE AND CONTROL
Chairman: Mr. S. Leek (UK)

Préguidage d'un intepteur longue porteé en phase de formage de trajectiore
(Long Range Guidance for a Homing Missile)
E. Meloux, P. Delpy — Aerospatiale, Espace et Defense, Les Mureaux, FR

ASRAAM - New Horizons in Air Defence
S. Leek, J. Tilsley — British Aerospace, Stevenage, UK

SESSION VII - C^3I ASPECTS
Chairman: Dr. D. F. Liang (CA)

<u>**Interaction Fusion de Données Communications: Evaluation de Principes d'Echanges entre Centres d'un C^3I sur le Champ de Bataille**</u>
(Data Fusion - Communc ation Interaction: Assessment of Data Exchange Principles Between Battlefield Command, Control, Communication and Intelligence Systems)
P. Guerchet, P. Germain, N. Blanchard, L. Aubert — Thompson-CSF, Bagneux, FR

<u>**Air Command and Control System (ACCS) Surveillance Exploratory Prototype (ASEP)**</u>
G. Retzer — SHAPE Technical Centre, The Hague, NE

ROUND TABLE DISCUSSION

The Challenge of Defending Against Ballistic Missiles

Dr. J. David Martin
Director for Strategic Relations
Ballistic Missile Defense Organization
The Pentagon
Washington DC 20301-7100

o The Emerging Ballistic Missile Threat

The proliferation of theater-range ballistic missiles armed with chemical, biological and nuclear warheads represents an existing, significant missile threat to deployed forces of the United States, its friends and allies. Ballistic missile deployments are expected to increase worldwide, despite stepped up efforts to inhibit their proliferation, and several countries other than the acknowledged nuclear states are developing both nuclear weapons and ballistic missiles. Similarly, a number of countries have or are developing chemical or biological weapons that could be delivered by ballistic missiles. Many potentially hostile nations now possess tactical ballistic missiles capable of targeting wide areas within Europe, the Middle East, South Korea and Japan. Concerted efforts are underway in several potentially hostile nations to enhance their tactical ballistic missile capabilities with longer-range missiles. These nations are developing indigenous missile production facilities, accurate missile delivery systems, and missile warheads with weapons of mass destruction. Of particular concern are those missile programs in Pakistan, Iran, Iraq, Syria, Libya, and North Korea -- all of which have or could develop weapons of mass destruction for use on their ballistic missiles. This growing comprehensive threat capability, coupled with the unpredictability of potential adversaries, represents a serious threat to vital United States national interests, and to those of NATO.

I would like to cite Mr. James Woolsey, the United States Director of Central Intelligence:

Ballistic missiles are becoming the weapon of choice for nations otherwise unable to strike their enemies at long range. Today there are 25 countries, many hostile to our interests. . .that are developing nuclear, biological, or chemical weapons. . .some of these countries may place little stock in the classic theory of deterrence which kept the Cold War from becoming a hot one. . .

A case in point is North Korea. In March of this year Mr. Woolsey noted that another challenge is North Korean development of ballistic missiles -- including those in the range of 1,000 kilometers and greater -- which can be made capable of carrying nuclear, chemical, or biological weapons. Although no exports have yet taken place, North Korea's traditional customers in the Middle East, such as Iran, are seeking these missiles, which could reach targets in Israel, Turkey, and Saudi Arabia.

The North Koreans are reportedly developing two additional missiles with ranges greater than the 1,000 kilometer missile that it flew last year. These new missiles have yet to be flown, but their development will be monitored, including any attempts to export them in the future to countries such as Iran. Unlike the missiles the North Koreans have already tested, these two -- if they are developed and flight tested -- could put at risk all of North East Asia, Southeast Asia and the Pacific area, and, if exported to the Middle East, could threaten Europe.

Presently, the Patriot system used during Desert Storm is the only defense against this rapidly evolving tactical ballistic missile threat. However, limitations of the Patriot system in a stand-alone role against a more capable developing ballistic missile threat has become a key concern for future conflicts. In response to this threat, Congress and the Clinton Administration have directed that the Department of Defense develop an accelerated program to counter the ongoing widespread proliferation of long-range tactical ballistic missile systems.

o The United States Ballistic Missile Defense Program

Following a fundamental overall review of U.S. national security strategy and future force structure -- the so-called Bottom-up Review or BUR -- conducted early in the Clinton Administration, the Department of Defense has decided, in the case of missile defenses, to give highest priority to Theater Missile Defense (TMD). The threat of shorter range missiles, as seen in Desert Storm, is where our principal near-term security concern lies. TMD, in our view, is intended to provide both protection for American military forces and those of our allies and coalition partners as well as for friends and allies themselves. Defense of the United States itself - or what we call national

missile defense - which was our principal concern in the days of the Cold War, now is a lower priority.

Congress has consistently demonstrated its strong support for the course the Department of Defense is pursuing with regard to Theater Missile Defenses. The Missile Defense Act of 1991, as part of the Fiscal Year 1992 Defense Authorization Act, stated that it is

"...a goal of the United States to provide highly effective theater missile defenses to forward deployed and expeditionary elements of the armed forces of the United States and to friends and allies of the United States."

The TMD program, moreover, is based on valid military requirements. This requirement, set forth by our Joint Chiefs of Staff (JCS), states that the United States is required to respond to the full range of theater missile threats that should include capabilities for both "near leak proof" defense of critical assets dispersed over wide areas integrated with capabilities for command, control and communications. The Bottom-up Review's sober assessment of the existing and emerging ballistic missile threats endorsed the programmatic response the Ballistic Missile Defense Organization embarked on as a result of the Missile Defense Act and JCS requirements.

Given this background, DoD's Ballistic Missile Defense Organization designed a comprehensive TMD program to achieve in-depth defense capabilities against Theater Ballistic Missiles (TBMs) with a spectrum of range and warhead capabilities. The mainstream program consists of two complementary basic thrusts: (1) upgrades to the existing Army Patriot and Navy Aegis Block IV A missile interceptor for terminal, or "last-minute", defense against TBMs with short to medium range, and (2) development of the Theater High Altitude Area Defense (THAAD) system to both provide a high-altitude overlay for the terminal defense systems and extend the battle space against long-range TBMs. The battle space is extended by intercepting attacking missiles at both higher altitudes and ranges that are much further away from the defended assets. This in-depth defense capability against the more capable, developing TBM threat is vital to minimize TBM leakage to the defended area from threat saturation attack strategies based upon synchronized launching of multiple missiles for the penetration of missile defenses. In addition, THAAD provides the capability for multiple shoot-look-shoot engagement opportunities due to its longer range capability. Simply stated, THAAD allows the defense to intercept attacking theater ballistic missiles early, often and further away from their intended targets. It represents a particularly significant, qualitative advance in the defense concept - the ability to provide for a wide-area defense.

Currently the THAAD program has achieved the design of the three basic components of the system: the THAAD missile interceptor; the supporting TMD ground-based radar; and the battle-management, command, control, and communications infrastructure. The THAAD program is employing advanced missile technologies that were developed in various BMD programs, and places emphasis on downsizing the THAAD interceptor for its rapid worldwide deployment by U.S. transport aircraft. The THAAD system is currently being developed in a Demonstration/Validation phase, which will include an extensive flight test program to validate the capabilities of the THAAD interceptor against simulated theater ballistic missile targets.

o Hit-to-Kill Interceptors - A Guidance/ Control Challenge

A system like THAAD provides a conceptual breakthrough by providing an area defense capability. Technologically, THAAD and the Patriot PAC-3 system (ERINT) demonstrate another major breakthrough i.e., hit-to-kill capability, where no warheads are now required onboard the interceptor. It has been a major guidance and control challenge for the interceptor community this past decade.

Theater ballistic missiles, particularly those that can carry chemical or biological submunitions, demand very high levels of lethality to provide the maximum protection to U.S., allied and friendly troops and targeted population centers. This lethality requirement places significant new demands on anti-tactical ballistic missile (ATBM) designs, particularly on their guidance and control.

ATBM interceptors functionally differ little from those that defend against aerodynamic threats; those functions, however, must be faster, more accurate, and be far more capable. These new or improved designs are particularly critical in two areas improved methods of terminal guidance that include target imaging and superior missile agility in the last seconds before intercept -- in the end game. Other functions such as propulsion, firepower, etc. can be improved with concomitant improvements in effectiveness and increased cost. ATBM effectiveness is governed by three key factors:

Target characteristics: TBMs have some unique characteristics that significantly differ from aerodynamic targets (the traditional air defense

threat). Threat missiles can have either separating or non-separating warheads (e.g., Scud, SS-21). While non-separating TBMs are similar in size to aircraft, their susceptible areas are localized to the forward end. Both types provide a much smaller susceptible cross section, on the order of 1-2 m^2; while aircraft are usually at least an order of magnitude higher. TBM velocities are typically two to ten times greater than high performance fighter aircraft. These size and susceptibility characteristics combined with the generally head-on engagements reduce the end game time to just a few seconds. While TBMs do not have the ability to consciously jink, there have been examples of unintended high-accelerations that have the same result.

Lethality requirements: There are several types of TBM warheads, including unitary and submunition, that must be countered. Each type has a measure of inherent resistance to damage to anything other than a direct impact. Conventional high-explosive unitary munitions may have thick exterior skins that can deflect or mitigate the effect of normal air defense warheads. Tests have shown that individual TBM submunitions can be damaged by fragments, but that many can survive intact and impact the target area. A direct hit by an interceptor with a mass of about 100kg can transfer three to five orders of magnitude greater energy into the threat warhead. While the lethality mechanisms and absolute effectiveness are still being debated the relative value of hit-to-kill is clear.

Missile characteristics: Very high levels of lethality favors hit-to-kill interceptors that in turn places unique demands on the ATBM's functional design. It requires in the endgame a seeker that can image the target, very high agility and precise control, and closed-loop guidance. The interceptor must not only directly hit the TBM, but must select the a priori designated warhead area. This requires an imaging seeker that can adequately resolve the target in time to compute the designated impact point. This necessitates a relatively short wavelength that can best be provided by either active millimeter wave radar or passive medium wave infrared. The processing must be fast and accurate enough to select the aimpoint.[1]

[1] While some sensor requirements are more stressing for the TBM threat, some are less. For example, ATBM seekers has greatly reduced requirement for clutter and background suppression than seekers designed for the aerodynamic threat at low altitudes.

The closure rates with the threat that ATBMs experience coupled with their relatively low signatures significantly shorten the engagement timeline. Errors that exist upon target acquisition must be very rapidly corrected. For missiles flying in the atmosphere and generating lift, the demands for agility and precise control are extraordinary. The interceptor must be laterally accelerated to place it on the proper trajectory and then decelerated to keep it there. Overshooting or hunting cannot be tolerated. The accuracies that are required are measured in centimeters not meters. Errors must be sensed, corrections computed, and the missile flown to the proper point all the way to the target. These actions require very fast onboard closed-loop guidance. Little or no latency time is available to transmit the TMB's position to the ground for processing an intercept solution as is done in many current air defense systems (e.g., HAWK, STANDARD).

In summary, the lethality requirements of tactical ballistic missile interceptors place great demands on the guidance and control functions. They mandate very high throughput flight data computers; accurate inertial measurement units and accelerometers; fast acting reaction or aerodynamic controls; and high resolution sensors. Finally, the integration and system engineering of all these subsystems must take into account the range of threats and environments expected and provide the best solution to the user.

o The BMD Program and the ABM Treaty

While our challenge in the BMDO is technical and programmatic, there are also policy factors that have an important bearing on the "way-ahead" in TMD. The DoD is planning to develop and deploy theater missile defense systems to counter the projected threat to our forces abroad and to our allies. This mission is well within the purposes and objectives of the ABM Treaty. The objective of the ABM Treaty is to enhance strategic stability by limiting defenses of the parties' territories against *strategic* ballistic missiles. The Treaty does not limit defenses against tactical or theater ballistic missiles, per se. However, the Treaty offers no concrete guidelines for distinguishing between ABM and non-ABM systems and strategic and theater ballistic missiles. This ambiguity is the subject of the Administration's current proposal in the Standing Consultative Commission, which meets regularly in Geneva, to clarify the Treaty by establishing the demarcation between ABM and non-ABM systems. Meanwhile, all of BMDO's testing and development activities remain compliant, within the narrow interpretation of the ABM Treaty.

o The Involvement of Allies

A key tenet in the U.S. TMD program is to develop missile defense capabilities in an evolutionary manner, e.g., upgrading TPS-59 HAWK systems, improving Patriot capabilities by deploying PAC-3, etc. The rapid expansion of the tactical ballistic missile threat argues strongly for accelerated deployment/upgrade of systems to provide more capabilities against longer-range tactical missiles. Modifications to existing systems can provide point, or small area, defense against most existing tactical ballistic missile threats. More advanced theater defense systems like THAAD, which are capable of defeating long-range theater missiles, would form the basis for upper-tier wide area defenses.

This strategy is being extended into our foreign discussions with those nations operating export versions of U.S. equipment, producing U.S. systems under license, or contemplating the possible codevelopment or acquisition of U.S. equipment in the future. The plan to coordinate the development and implementation of TMD programs with friends and allies has the goal of avoiding duplication, reducing costs, and increasing interoperability.

This plan is an evolutionary approach that builds on the success of earlier programs, to include those sponsored by external organizations such as NATO. The plan proceeds from a foundation where the responsible political and military authorities set forth the need for defenses. Coordination is effected (e.g., by the NATO Air Defense Committee) to ensure that TMD is properly integrated into the existing air defense and airspace command/control systems. The plan draws on the results of numerous baseline analyses such as NATO's Advisory Group on Aerospace Research and Development (AGARD), the NATO Industrial Advisory Group (NIAG), and BMDO supported missile defense architecture studies for Europe. It includes the definition of technology alternatives as identified in these baseline architecture studies. As individual nations complete their own studies (like those in the United Kingdom and France), bilateral discussions provide the basis for future cooperative actions.

The near-/mid-term program identifies the potential for relatively rapid, low cost, feasible improvements to existing systems and or operational concepts that will result in measurable improvement in early warning and TMD capability.

The far-term plan will build on these near/mid-term improvements with the objective of further enhancing lower tier capabilities and adding the upper tier capability. The potential for foreign involvement in the development of a new system for the far-term, and the magnitude of such involvement, will vary depending upon the status of the program, i.e., where it is the acquisition process. A key determinant will be the timeframe that the United States and individual nations engage in discussions on participation in the program. The United States attempts to initiate bilateral discussions as early as possible in a new system's development cycle. This process is one subject to mutual negotiation and agreement, and thus of necessity somewhat variable.

o Concluding Comments

The United States is embarked on an agressive program in Theater Missile Defense designed to put "rubber on the ramp" as soon as possible so that, when the next crisis arrives, Americans and coalition forces will be better protected than was the case during Desert Storm. The requisite technical challenges, like hit-to-kill concepts, which have been built on the significant new capabilities put forward by the guidance and control cummunity annually, have now been met. The NATO allies and Japan, like the U.S., may be faced with this same future problem, defending its military forces, or perhaps even their homelands against ballisitic missile attacks. Our defense budgets today preclude each of us from working the problem separately. We must work together to meet the threat and the economic necessity.

NATO INDUSTRIAL ADVISORY GROUP (NIAG)

STUDY ON EXTENDED AIR DEFENCE POST 2000 (EAD-2000)

Peter J. Mantle
Chairman, NIAG SG-37

Director, European Programmes
Defensive Missile Systems
Lockheed Missiles & Space Company
1111 Lockheed Way
Sunnyvale, California 94089, US

1.0 INTRODUCTION

In 1991, NIAG SG-37 conducted for the NATO Industrial Advisory Group (NIAG), under the sponsorship of the NATO Army Armaments Group (NAAG), an assessment of the Air-Land Battle for Allied Command Europe (ACE) in the Post 2000 time period. This assessment was specifically directed at conducting a Technology Forecast of the *Key Technologies* that would enable *System Concepts* solve particular deficiencies foreseen in the NATO defensive systems. This assessment was called Technology Forecast Post 2000 or TF-2000 (Ref 1). After the completion of the work, it was decided that NIAG SG-37 would direct its efforts toward a specific part of the Air-Land Battle devoted to *Extended Air Defence (EAD),* i.e.conventional air defence (against aircraft and cruise missiles) plus the extension to defence against ballistic missiles. This effort conducted during 1992/1993 was sponsored by the NATO Air Force Armaments Group (NAFAG) and is the subject of this paper.

Specifically, NIAG SG-37 used the same methodology for this effort on Extended Air Defence as that used for the TF-2000 work. That is to say, after re-examining the geopolitical situation that faced Europe, updated the System Concepts from TF-2000 that solved NATO perceived deficiencies and identified the Key Technologies deemed necessary to bring these System Concepts into being. Again, as for TF-2000, after determining the military cost-effectiveness of the System Concepts, NIAG SG-37 prepared R&D Programmes recommendations with particular emphasis on those that were identified as being most suitable for international collaboration.

These recommendations are provided for: PEACE, CRISIS and WAR in the four geopolitical scenarios: THEATRE, REGIONAL, BORDER and for OUT of AREA operations. This last category was added to the original geopolitical scenarios in recognition of the new unrest in the world and in NATO's new role in the defence of Europe and its interests outside of contiguous Europe. This paper is a summary of the main results on EAD-2000. The full report may be found in Ref. 2.

Related Studies

As a measure of the concern in light of recent world events, several groups within NATO have been charged with examining complementary aspects of EAD. These include AGARD AAS-38, concentrating on the architectural aspects of tactical ballistic missile defence (one important part of EAD), and DRG RSG-16, concentrating on the C^2 aspects of the broader EAD.

In this context, the NIAG SG-37 effort has concentrated on those particular *System Concepts* and *Key Technologies* that apply to EAD. In addition to these groups that are concentrating on the various sub-sets of Extended Air Defence, there is the "sister" NIAG group NIAG SG-47, that has been charged with using the TF-2000 methodology to Maritime Warfare which includes defence of ships against cruise missiles. Where there are interfaces between these groups in the area of EAD, coordination has been accomplished to ensure synergy of effort. In its work, NIAG SG-37 also interfaced with NATO organisations such as the NATO Air Defence Committee (NADC) and its subordinate panels (PADP and PADW); the SHAPE military staff and the SHAPE Technical Centre, among other groups involved with Extended Air Defence.

2.0 SUMMARY RESULTS

A primary objective of the EAD-2000 study was to make recommendations on R&D Programmes for the successful development of an Extended Air Defence system for NATO Europe and NATO forces.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

To ensure that the R&D Programmes address technologies that support military needs, it was necessary to first develop System Concepts. It was convenient for ease of management, to group these System Concepts into four (4) groups:

I	Early Warning & Detection
II	BM/C^3 Systems
III	Engagement Systems
IV	Crisis Management

Figure 2-1 shows these thirteen System Concepts. Section 5.0 provides more detailed description. In order to bring these System Concepts into being it was found that there was a need for development of certain technologies. Some of the technologies were at an engineering level stage and others were in early stages of development. Those technologies that were key to the success of the System Concepts and were not under active development in some nation of the Alliance were particularly given attention. Twenty-one (21) Key Technologies were identified. These Key Technologies formed the basis of the R&D Programme recommendations. For ease of management and clarity of presentation, these Key Technologies were grouped under eight (8) headings:

1	Computers
2	Software
3	Sensors
4	Communications Network
5	Electronic Devices
6	Materials & Processes
7	Energy Storage & Lethality
8	Propulsion

GROUPING	SYSTEM CONCEPT		Expected IOC
EARLY WARNING & DETECTION	101	Early Warning Satellites	2000
	102	High Altitude Surveillance Aircraft	2000
	103	Medium Altitude Surveillance Aircraft	2000
	104	Skywave & Surface Wave HF Radar	2000
	105	Modular UHF Radar	2005
	106	Transportable L-Band Radar	1998
BM/C^3 SYSTEMS	114	BM/C^3 Systems	2000
ENGAGEMENT SYSTEMS	108	Endo-Exoatmospheric Missile Systems	1998
	109	Endoatmospheric Missile Systems	2000
	111	Aircraft Based Interceptor	1998
	112	Directed Energy Weapons	2005
	113	Kinetic Energy Weapons	2010+
CRISIS MANAGEMENT	115	Crisis Management Systems	2000

Figure 2-1: EAD-2000 System Concepts

Details of the twenty (20) R&D Programmes identified to develop the Key Technologies is provided in Ref 2. There is a range of development times required depending on whether the System Concepts were using existing or emerging technologies or whether the Key Technologies were in an early stage of development. This is reflected by the range of dates required to reach Initial Operational Capability (IOC) of the System Concept. As in TF-2000, the end of prototype development and the first operational use of the system is taken as the end of the R&D phase. An indication of the total R&D costs (including prototype development where appropriate) is provided in Figure 2-2.

Figure 2-3 shows the list of twenty one (21) Key Technologies grouped into the eight (8) Technology Categories. To provide an indication of the relationship between the Key Technologies and the System Concepts a cross reference is provided in Figure 2-3 to the System Concepts listed in Figure 2-1. Also, reference is shown for the pertinent R&D Programme Sheets. Details of these R&D Programme Sheets is provided in Ref 2.

Operational Considerations

In addition to conducting analyses on System Concepts and Key Technologies, NIAG SG-37 also examined the Operational Considerations of the System Concepts. A brief synopsis of the System Concepts is provided in Section 5.0. The results of that Operational Considerations analysis were grouped under the following headings:

Lethality Constraints on Missile Intercepts
Separation and Forward Basing of Assets
Multi-National Sharing of Assets
Boost Phase Intercepts
Shipborne Operations
Cueing and Handover
Airborne Operations
Strategic Positioning

Summaries are given in Section 6.0 of this paper.

TECHNOLOGY GROUPING	APPROXIMATE R&D COSTS	EXPECTED IOC
1 COMPUTERS	<$200M	1998 - 2000
2 SOFTWARE	$200M	1998 - 2005
3 SENSORS	$500M	1998 - 2000
4 COMMUNICATIONS NETWORK	$500M	1998 - 2005
5 ELECTRONIC DEVICES	$1.5B	1998 - 2005
6 MATERIALS & PROCESSES	$100M	1998 - 2005
7 ENERGY STORAGE & LETHALITY	$1.5B	1998 - 2010+
8 PROPULSION	$200M	2000

Figure 2-2: R&D Programmes Costs and Duration

TECHNOLOGY CATEGORY	KEY TECHNOLOGY		SYSTEM CONCEPT Applicability	R&D Prgm Sheet
Computers	i	Massively Parallel HPC Systems	104	20
	ii	Rapid Signal Processing Upgrade Capability	108, 109	20
	iii	Automatic Neural Networks	114	20
Software	iv	Data Fusion	108, 109, 114, 115	1
	v	Expert Systems	108, 109, 114, 115	5
	vi	Atmospheric Characterisation Codes	112	12
Sensors	vii	High Resolution Focal Plane Arrays	101, 102, 108, 109, 111	13
	viii	Improved Discrimination Techniques	104, 108, 109	15, 18
	ix	NCTR Techniques	108, 109	3, 18
	x	Common Aperture RF/IR	103	2
	xi	Conformal Antennae	103	16
Communications Network	xii	Interoperability	108, 109, 111, 114, 115	4
	xiii	Secure Accessible Communications	103, 108, 109, 111, 112, 114, 115	19
Electronic Devices	xiv	Power Added Efficiency for Radar	103, 106, 108, 109	6
	xv	Laser Beam Director	112	12
	xvi	IR Detector Improvements	101	17
Materials & Processes	xvii	High Speed Radomes and Windows	108, 109, 111, 112	8, 9
	xviii	Lightweight Robust Structures	102, 103, 106	7
Energy Storage & Lethality	xix	Improved Warhead Techniques	108, 109, 111	11
	xx	Improved Switches	113	14
Propulsion	xxi	High Efficiency Propulsion Techniques	102, 103	10

Figure 2-3: Key Technologies for EAD

3.0 METHODOLOGY & STUDY DRIVERS

The methodology used for EAD-2000 mirrors that used for TF-2000 (Ref 1). Various changes have occurred on the geopolitical scene since the 1991 effort on TF-2000, and these have been taken into account in the current effort on Extended Air Defence. The basic method, however, remains unchanged. As before, there were several "study drivers" that influenced the sub-group's deliberations. These study drivers include the contract Objectives and Deliverables as called for in the Terms of Reference (TOR) but they also include the continually unfolding events in the world that is influencing the role and charter of NATO. The new role in Out of Area (OOA) operations has influenced the study's work and recommendations. These study drivers are summarised here.

PEACE, CRISIS and WAR in a new Geopolitical Europe

The geopolitical scene for Europe was unfolding during the TF-2000 effort and continues to change today. The three geopolitical scenarios of THEATRE, REGIONAL and BORDER treated in TF-2000 are still valid and retained in the EAD-2000 evaluation. In light of the changing role of NATO, it was agreed with the sponsor (NAFAG) and other NATO offices to add a fourth geopolitical scenario called OUT of AREA.

The following descriptions of the geopolitical scenarios were used for EAD-2000:

THEATRE
This geopolitical scenario is characterised by Central Europe with a buffer zone created between NATO countries and the former Soviet Union, caused by the collapse of the Warsaw Pact. Such a buffer zone, 500-1000 km, made up of countries with their own priorities on defence will impact NATO's plans for the security of Europe. There is the possibility of new postures and alliances between ex-Warsaw Pact countries and the new Commonwealth of Independent States.

REGIONAL
This geopolitical scenario reflects the edges of NATO that embody (a) the Northern Region where Norway is adjacent to Soviet territory and (b) the Southern Region that is adjacent to areas of heightened concern. This Southern Region includes the territory of predominately Islamic communities that extends from the Western edges of the North coast of Africa to the borders of Turkey. It also includes the edges of Turkey that are adjacent to the Republics of Armenia and Georgia.

BORDER
This geopolitical scenario is in a sense, recognition of how today's technology explosion has given new meaning to the old border incident where a sudden cross-border skirmish or terrorist action has impacted a country. The technology expansion in the world, especially missile technology, now means that a non-major power in the world can threaten NATO from a distance. The isolated missile attack by Libya on Italy in 1986 would be an example of possible new border incidents or long range terrorist action.

OUT of AREA
This geopolitical scenario represents both the new concerns of NATO in protecting its overseas interests and NATO action in support of the United Nations. The recent use of forces from NATO countries to assist the United Nations relief work in Somalia is an example of the latter. An added complication of this type of scenario is the involvement of non-NATO forces. There may be difficulties in cooperation, for example if the communications systems are not interoperable.

These broad geopolitical scenarios and the three phases of PEACE, CRISIS and WAR, became the so-called "twelve cell matrix" shown in Figure 2-4

Relating Technologies to Military Needs

The methodology used is the same as that used for TF-2000. The key driver in the approach has been to ensure that the NATO planner when using this report could audit the recommended R&D Programmes (and the associated Key Technologies) back through to a NATO military need in the postulated geopolitical scenarios in PEACE, CRISIS and WAR.

A key feature here is that if there is a change in military priority, or geopolitical scenario, or other change, the NATO planner could determine from the NIAG SG-37 approach how to interpret and use and modify, if need be, the results.

Accordingly, the same nine step approach was used, which is reproduced in Figure 2-5.

	THEATRE	REGIONAL	BORDER	OUT of AREA
PEACE				
CRISIS				
WAR				

Figure 2-4: EAD-2000 Geopolitical Scenarios (The Twelve Cell Matrix)

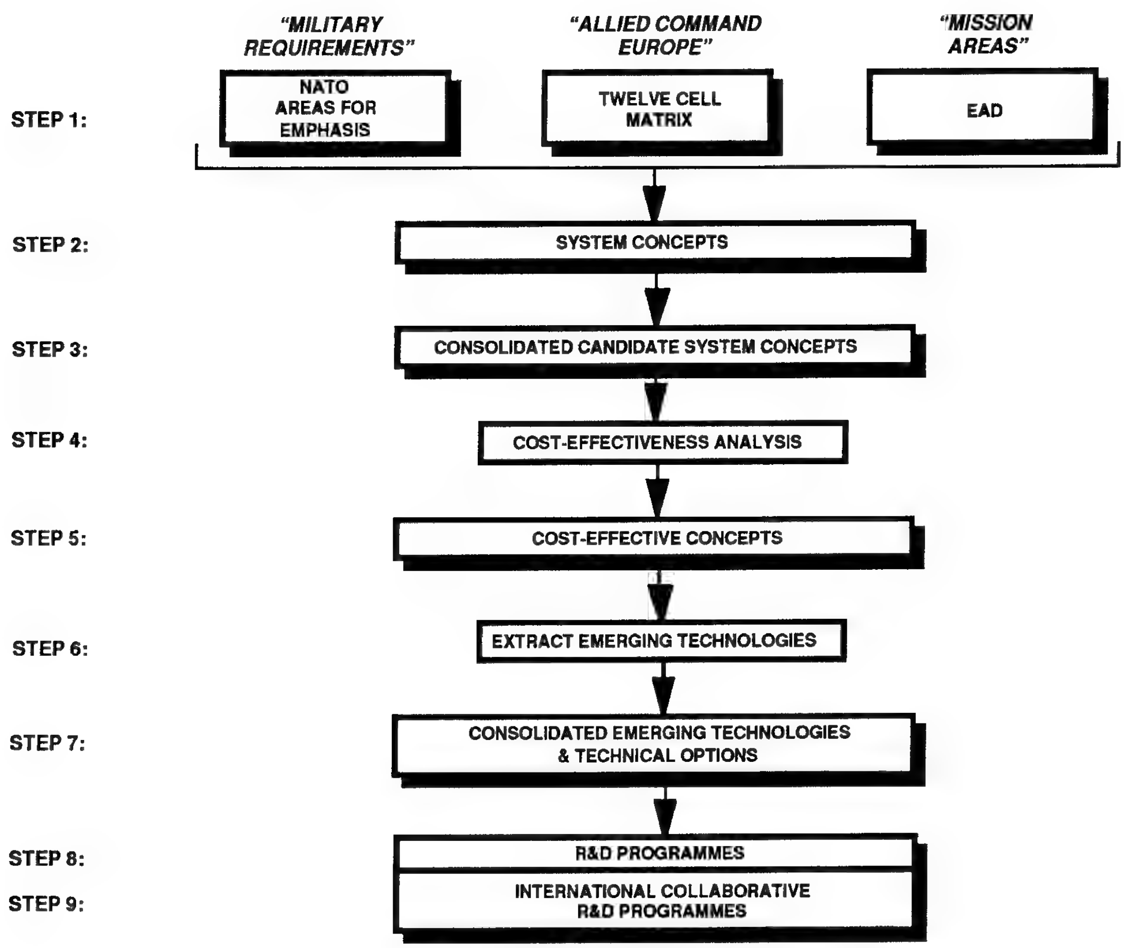

Figure 2-5: EAD-2000 Study Approach

4.0 GEOPOLITICAL and THREAT ENVIRONMENT

The geopolitical situation up to the end of 1991 was analysed in the NIAG SG-37 TF-2000 report (Ref 1). This was updated for EAD-2000. There have been several significant changes since 1991. In spite of the success of NATO and UN forces in the Gulf War, Iraq remains a risk area and it is believed that Iraq is attempting to rebuild its ballistic missile inventory. Warfare has broken out in the former Yugoslavia and in Somalia. North Korea and China continue to develop long range ballistic missiles (approx 2000km and longer). The cruise missile has become a new threat with ROW inventories approaching those of the ballistic missile. Nuclear weapon capability continues unabated through technology transfer and other means. Also, NATO forces continue to draw down and economic problems are of concern throughout the Alliance.

Beginning before the end of the Cold War and accelerating in pace from the onset of the Gulf War, has been the proliferation of sophisticated weapons around the world. This proliferation has been both in production and sales of hardware and in technology transfer to nations that are not necessarily friendly to the Alliance or the FSU. It is gradually being recognised that the development of *tactical* ballistic missiles is now reaching the performance levels once associated with *strategic* missiles. This has already complicated the treaty issues among those nations seeking to limit strategic missile systems development, testing and deployment.

A new concern is that the cruise missile is also beginning to proliferate, with inventories being of similar magnitude to the tactical ballistic missile worldwide inventories. NIAG SG-37 explored the threat (risk) environment with cognizant bodies and coordinated with the NATO organisations, SACEUR; SHAPE and others for a set of known and likely threats through the years 2010+. Also, as part of the coordination with other NATO groups working on EAD (see Introduction), the threat data was checked across the groups and found to be compatible. Figure 2-6 is the (unclassified) description of the EAD threats (i.e. TBM, CM and A/C) used in EAD-2000.

Of immediate concern is the ballistic missile. Figure 2-7 shows the typical characteristics of interest to the defender. Just the minimum energy (maximum range) trajectories are shown.

These ballistic missile trajectories are representative of today's missiles from the SS-21 (100km) to the CSS-2 (2000^{+}km) to the CSS-4 (3000^{+}km range) missile. Other known threat missiles have similar range capabilities.

THREAT	SPEED	ALTITUDE	NEAR TERM [1] (1995+)	MID TERM [2] (2002+)	FAR TERM [3] (2010+)
Short Range TBM (<1000 km)	1 - 3 km/sec	10 - 250 km apogee	• No manoeuvrability • No saturation • Small target - no design signature reduction	• Possible homing & manoeuvrability • Signature reduction	• Manoeuvrability • Signature reduction • Possible penaids
Long Range TBM (1000 <range <3000 km)	2 - 5 km/sec	100 - 550 km apogee	• Non separable RV • No manoeuvrability • Small target - no signature reduction	• Separable RV • Low manoeuvrability • Some signature reduction	• Possible high RV manoeuvrability • Multiple RVs • Possible Penaids
Subsonic CM	< Mach 1	30 m	• External acquisition • Basic unitary warhead • Some signature reduction	• Possible submunitions indigenous R&D • Significant signature reduction	• Indigenous R&D • Submunitions • Advanced signature reduction
Supersonic CM	< Mach 3	Low: 30 m High: 30 km & Dive	• None deployed but interest shown	• Possibly deployed • Significant signature reduction • Possible submunitions	• Probably deployed • Full stealth • Submunitions
Aircraft (including ALSOW)	< Mach 3	< 30 km	• Includes ASMs, UAVs • No stealth	• Includes ASMs & UAVs • Limited stealth	• Possible full stealth

[1] HE warheads
[2] HE, chemical, nuclear waste warheads
[3] HE & NBC warhead options

Figure 2-6: The Unfolding EAD Threats

RANGE (km)	V_{bo} (km/sec)	BOOST PHASE (secs)	FLIGHT TIME (mins)
120	1.0	16	2.7
500	2.0	36	6.1
1000	2.9	55	8.4
2000	3.9	85	11.8
3000	4.7	122	14.8

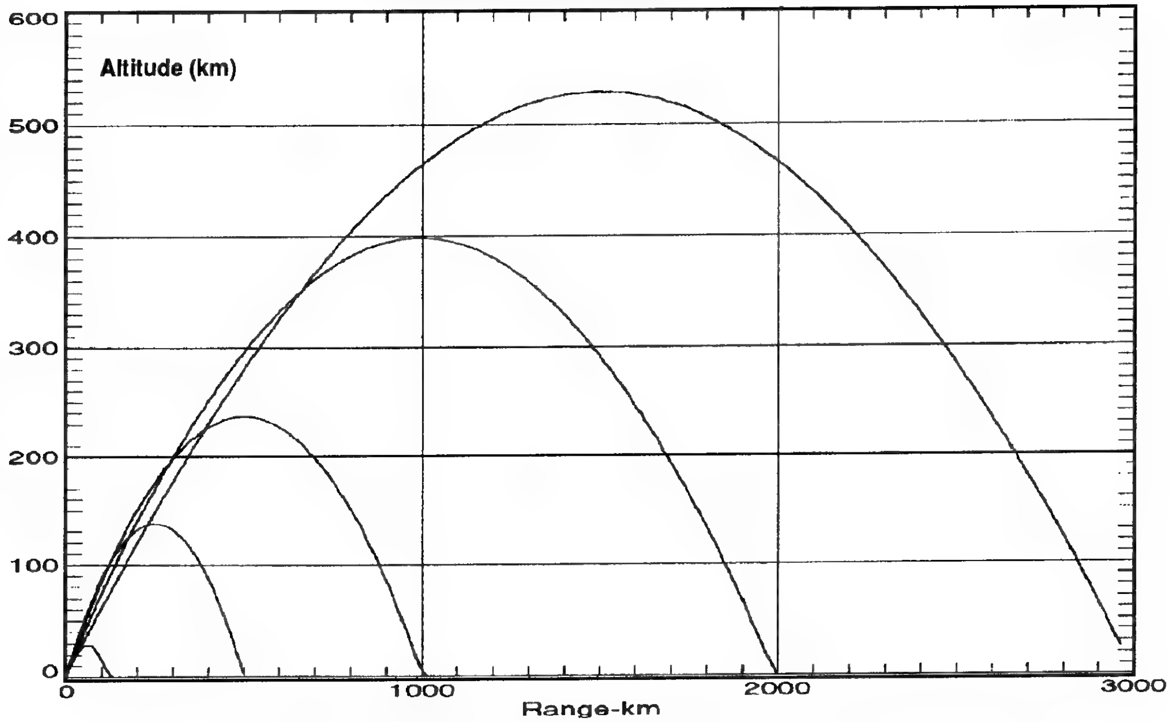

Figure 2-7: Typical Ballistic Missile Trajectories

Using these typical trajectories (calculated on certain acceleration paths through the atmosphere followed by ballistic trajectories through space) one can see the nature of the problem facing the NATO defender. The missile speeds range from 1-5km/sec; the flight times range from 3-15 minutes and the burn or boost phase time is from 16-122 seconds! Such short timelines will stress today's defensive systems and introduces many complexities into the proposed systems. In many instances it introduces non-"man-in-the-loop" systems and extremely fast computational techniques in signal processing and other complications that has driven many of the *Key Technology* and *R&D Programme* recommendations. The speed of the incoming warhead will, at speeds approaching 5km/sec in the coming decade, stress the design of interceptors and radars. Not shown in Figure 2-6, the RCS of the warheads will limit the range of detection of the radars and also will greatly increase the difficulty of intercept. The atmosphere extends from the earth's surface to altitudes 35-100km. From Figure 2-7 it is seen that this is only a small portion of the missile trajectory but it has significant impact on seeker and window design. This has driven several of the R&D Programme recommendations. Many of these concerns are applicable to the cruise missile threat.

Figure 2-7 shows just the minimum energy trajectories to be representative of the ballistic missile threat. Not shown are the other characteristics that are required to obtain a complete understanding of the threat. This includes the

manœuvring characteristics of the incoming warhead; the mass of the warhead and whether it is a unitary warhead or made up of submunitions and other parameters that must be considered. Each of these characteristics are discussed in Ref 2.

It is known that it is not possible today to determine if the incoming warhead contains HE, chemical or biological materials, or nuclear waste or a combination. For HE warheads, the signature is a key parameter; for chemical or biological warheads the mass of the warhead is important. Each of these parameters are discussed in more detail in Ref 2 as are discussions on the new threat of concern namely the cruise missile.

5.0 SYSTEM CONCEPTS

As stated in the Introduction, in order to provide recommendations on R&D Programmes, it was first necessary to put forward System Concepts to satisfy "military requirements" to avoid putting forward a set of technological developments without any perceived military need. The System Concepts were specifically constructed to solve various issues foreseen in Extended Air Defence. These thirteen (13) System Concepts were derived from the set put forward in the TF-2000 study and refined with later information and combined where necessary to form "system solutions". Complete details of the System Concepts are given in Ref 2. A synopsis of the main features of the System Concepts follows:

Early Warning Satellites (101)
Three options are proposed for Early Warning satellites. They are, (1) a LEO satellite system that is launched "on demand" say during a CRISIS; (2) a LEO satellite system permanently in orbit at approx 1000km altitude, and (3) a GEO satellite system at approx 36,000km altitude. All three provide different capabilities in early warning and other functions. All three systems are evaluated

High Altitude Surveillance Aircraft (102)
This is a very high altitude (approx 25km), long endurance aircraft for surveillance purposes and to look deep into enemy territory. It is evaluated in either of two versions; (1) an aircraft equipped with EO sensors, or (2) multimode phased array radar.

Medium Altitude Surveillance Aircraft (103)
The medium altitude (approx 12km) aircraft is designed to detect and locate enemy missile launchers and to provide recognised air picture for NATO command. Because of the sophistication and size of the various payloads it may be necessary to outfit two different aircraft for the complete mission.

Skywave and Surface Wave HF Radar (104)
The Skywave radar operating in the HF band detects low signature targets at long range (approx 4000km) by bouncing off the ionosphere. The Surface wave HF radar operates over water at ranges out to approx 350km. Both systems are evaluated.

Modular UHF Radar (105)
This radar operating in the UHF band is designed to detect the launch of ballistic missiles (at approx 1500km range) and track them through mid-course. It is also conceived to track low signature aircraft and cruise missiles. The radar is designed to be modular in construction for ease of transportability and set-up in the field.

Transportable L-Band Radar (106)
The L-Band radar (NATO D-band), with a range of approx 1000km, is designed to detect TBM, aircraft and cruise missiles. It is also designed to be small enough to be suitable for shipborne operations.

BM/C^3 Systems (114)
The current BM/C^3 systems within NATO are designed for the air breathing threat and are limited to 35km altitude. The proposed system expands the BM/C^3 network out to 400km altitude. It is proposed that improvements be added to the current system to handle the upgraded air breathing threat and that new functions need to be added to accommodate the TBM threat.

Endo-Exoatmospheric Missile Systems (108)
Various refinements are proposed to the endo-exoatmospheric missile system to handle the long range TBM threat (100-3000km range). The protected footprints are in the range of 30-200km radius. The operational envelope extends into the exoatmosphere regions (see Figure 2-7).

Endoatmospheric Missile Systems (109)
The endoatmosphere missile systems, designed for the air breathing threat, are evaluated in three subsets because of the different operational and technology differences in each; they are (1) the SHORAD designed to handle the short range threat (out to approx 10km); and (2) the medium range or MSAM system designed to provide protection at ranges measured in tens of kilometres and (3) a high endoatmosphere missile system designed to overlap with the endo-exoatmosphere missile system (SC 108) to provide complete multi-layer defence.

Aircraft Based Interceptor (111)
This is an airborne interceptor that is evaluated in two versions; (1) an interceptor with air-to-air weapon capability to intercept TBM in the mid-course or re-entry phase , and aircraft and cruise missiles in flight, and (2) an interceptor equipped with air-to-ground weapons for the destruction of TBM launchers on the ground or possibly intercepts of TBM in boost phase. The radius of operation is approx 150km.

Directed Energy Weapons (112)
Directed Energy Weapons are evaluated both in the soft kill mode, where say missile seeker windows and aircraft canopies are made opaque, and in the hard kill mode where structural damage is inflicted on aircraft, cruise missiles and TBM sufficient to destroy them. Both CO_2 and DF lasers are examined.

Kinetic Energy Weapons (113)
Although considered to be operational outside the foreseeable future (2010^+), kinetic energy weapons are evaluated because of their potential and as an alternative to the DEW. Both electrothermal (ET) and electromagnetic (EM) guns are evaluated.

Crisis Management Systems (115)
A consideration is provided on possible solutions to the important need for a Crisis Management system that can operate in PEACE and CRISIS in such a manner as to possibly avert WAR or at least interface the civilian crisis management functions with wartime functions. Consideration is given as to how a Crisis Management system can interface with the established Data Fusion Centres within the BM/C^3 systems.

6.0 OPERATIONAL CONSIDERATIONS

After the System Concepts had been derived, it became clear that several of them offered certain advantages when placed in new operational contexts. Although an exhaustive operational analysis was not applied, given the time and budget constraints, it was possible to conduct a top level analysis of the *operational considerations* in many of the areas of interest. A brief synopsis follows on some of the operational considerations.

Lethality Constraints on Missile Intercepts

Much has been published on the "footprints" of various missile interceptor systems. Figure 2-8 shows footprints for a representative interceptor system (Vbo=2km/sec; radar range=500km) defending against a 2000km class TBM. For this example, the interceptor and radar are collocated at a site (Point A) in the south of France. A trajectory is shown where the targeted Point T has been avoided with an intercept at Point I.

Typically, for "best" lethality, closing speeds of greater than 2km/sec and crossing angles less than 50-100 degrees are required. The wide range in crossing angles reflects the wide range of technological solutions to the type of threat (e.g. hit-to-kill, warhead fusing, unity or sub-munition warheads, chemical warheads, etc., etc.). As can be seen from Figure 2-8 (shown overleaf) such considerations significantly influence the size of the protected footprint for any given system. This, in turn, significantly affects the number of interceptor sites required for any given nation; especially since the direction of the threat has now taken on a variable nature in the light of world events (see Section 3.0 on geopolitical scenario discussion). Accordingly, from an operational consideration viewpoint, this implies several strategically located sites with overlapping footprints to offset the angle constraints shown in Figure 2-8. Of course, such a positioning of interceptor sites brings with it the complication of BM/C^3 networks.

Separation and Forward Basing of Assets

The separation of interceptors and radars was found to have a significant advantage for Wide Area protection, say for the protection of the civilian population, of any particular nation. Similarly, it was found that the forward basing of the sensor was also of distinct advantage. Figure 2-9 illustrates this for the example of the interceptor (Vbo=3km/sec and 2km/sec) located at Otranto, Italy and the radar (with range of 500km) located at Palermo, Sicily.

Note, for simplicity of presentation, the lethality constraints as shown in Figure 2-8 have not been drawn in Figure 2-9. A sample trajectory is shown on Figure 2-9 which now shows the point of radar detection at its projected slant range (Point D) The advantages of these types of operational considerations points out the increase in protected footprint area by separation of the interceptor and radar and further it provides the ability to "tailor" the footprint to fit the particular geography of the nation to be protected. Also, the forward basing of the radar has significantly increased the size of the footprint, meaning that less interceptor sites will be required to protect the country and thus less cost. In Figure 2-9, it can be visualised that if lethality constraints of the type shown in Figure 2-8 are incorporated into the footprints shown then it is possible that the footprints would shrink to where

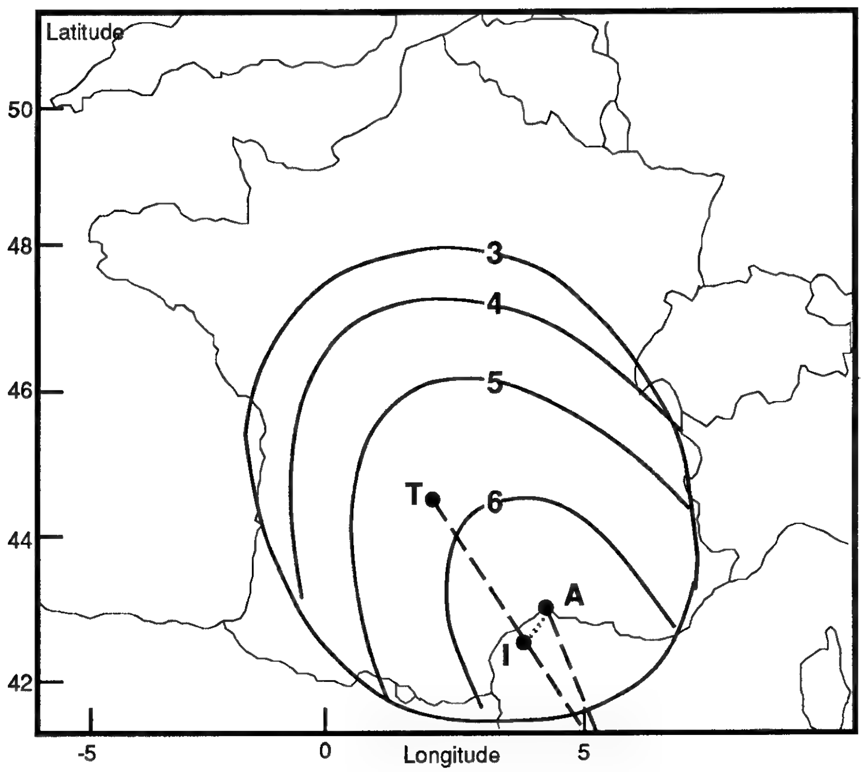

Figure 2-8 (a) Closing Speed

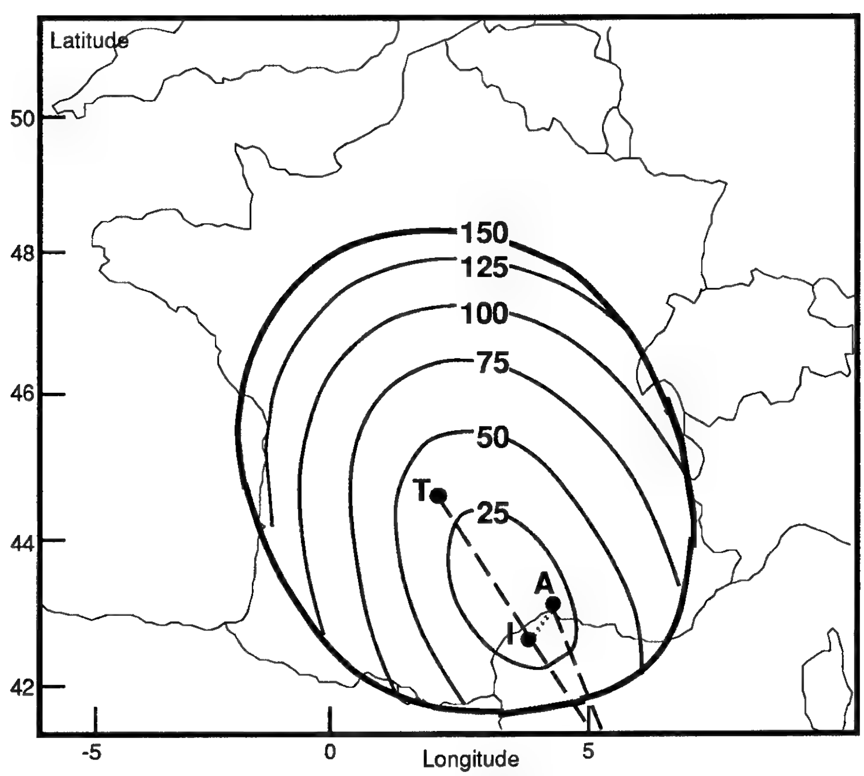

Figure 2-8 (b) Crossing Angle

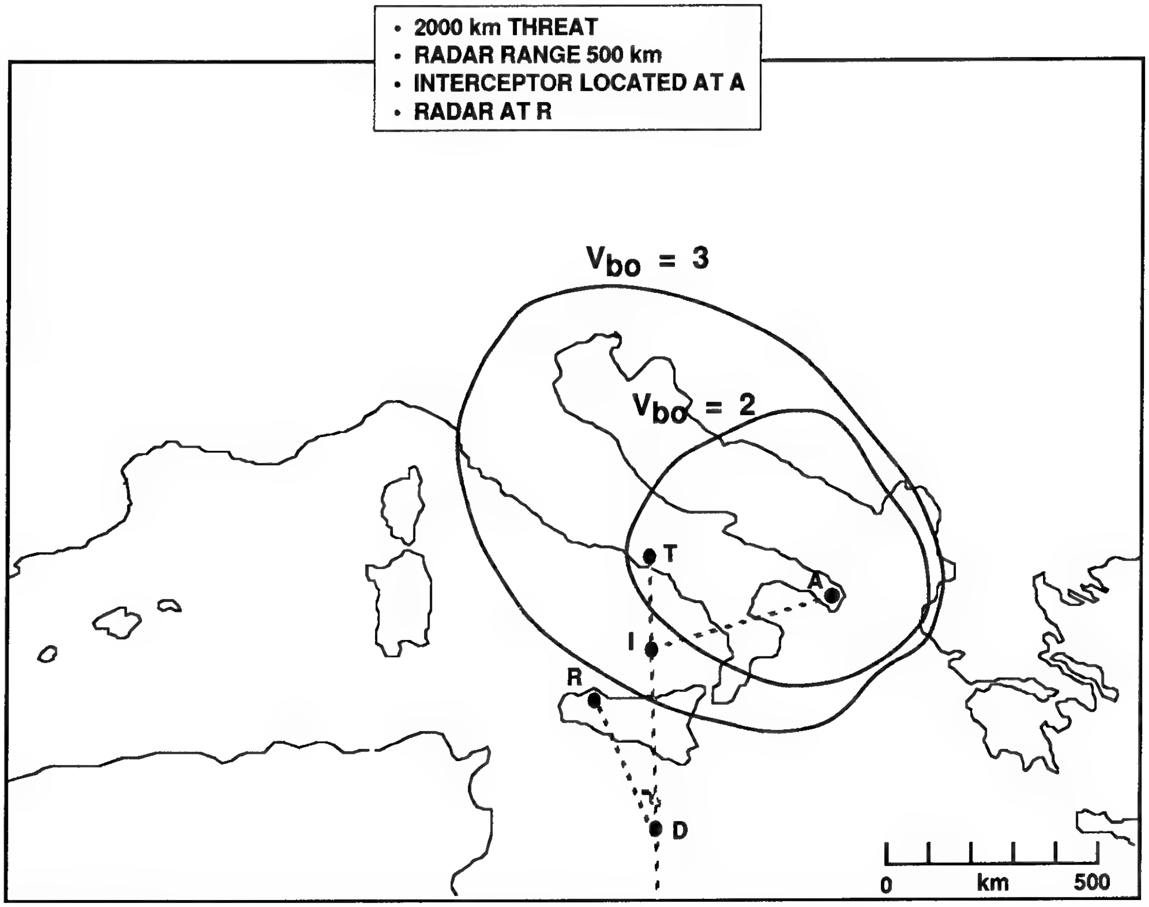

Figure 2-9: Effect of Separation of Interceptor and Radar

just Italian territory would be covered and would not change the effectiveness of the system. While not shown in Figure 2-9, but covered in more detail in Ref 2 is the possiblity of placing the interceptors or radars on ships that patrol the Mediterranean and provide a forward basing. Such considerations shows definite advantages to the footprint area. Also, as the threat axis changes then of course the ships can reposition themselves to again tailor the footprint to match the threat. The reader is reminded that the radar detection range is the slant range. Thus using the scale at the bottom of Figure 2-9 one can determine the altitude of intercept which for this example is quite low, but still above the 15-20km altitude limit set to intercept a chemical warhead. Ref 2 provides more analysis of defence against chemical warheads.

Multi-National Sharing of EAD Assets

A specific set of analyses was conducted to determine the feasibility of expanding on the above operational considerations to a multi-national scenario. Figure 2-10 shows one example of the sharing of one radar site among four (4) interceptor sites to protect one or more nations . In this example, Italy was chosen to illustrate the possibilities. It should be noted that the analyses were conducted just for the upper or outer layer of defence against the long range TBM (in this example a 2000km range missile coming from central Libya).

It is taken as a given that each nation would still have to strategically locate many Point Defence sites to protect specific assets such as military sites, airfields, power stations, etc. The analysis shown here is illustrative for the outer layer only. In the example shown in Figure 2-10 the radar is at Palermo, Sicily. The three interceptor sites are at A_1 in Sardinia; A_2 near Turin; A_3 in Palermo and A_4 on the western coast of Greece. Both the"shoot" and "shoot-look-shoot" boundaries are shown.

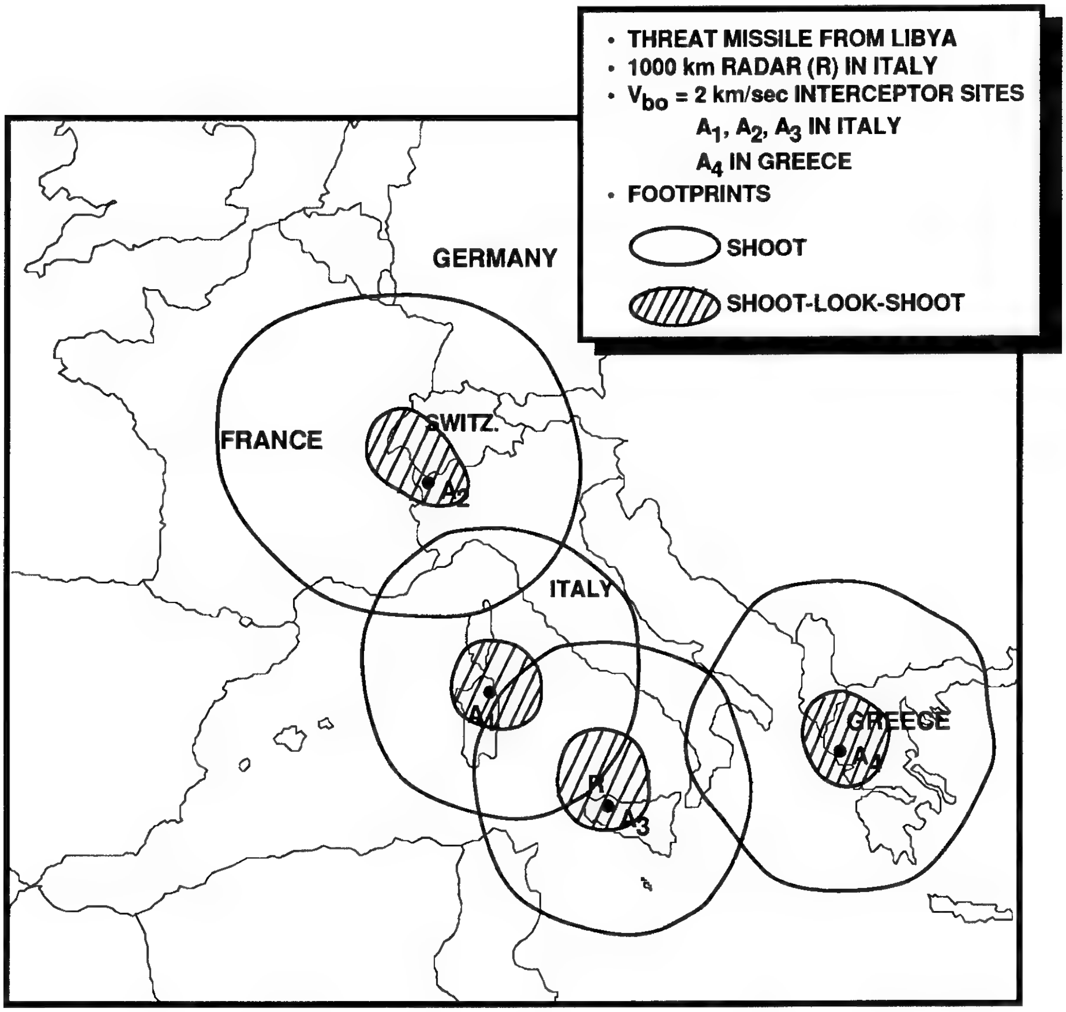

Figure 2-10: Benefits of Sharing Wide Area Defence

Several points can be made from Figure 2-10. All of Italy is protected by the four sites. In a more detailed analysis, where lethality constraints are included more sites would be required for complete coverage. More importantly because of the size of the protected areas, it is immediately seen that other nations such as Greece, Switzerland and parts of France and Germany are also protected. Accordingly, in putting together an EAD system for Europe considerations such as those shown here can be incorporated into the plan and the cost burden on each individual nation can be significantly reduced. Issues that have to be resolved are the interoperability of the systems, the design of the multi-national BM/C^3 system and the protocol of firing doctrine among the protected nations. Such solutions lend themselves to an integrated NATO command structure that takes into account the national interests.

Boost Phase Intercepts

Considerable attention was given in the study by NIAG SG-37 on the subject of boost phase intercept. There were several reasons for this. First, it is recognised that even with the projected performance levels of interceptor systems over the next two decades and with the projected performance levels of long range radars (cued or uncued) most of the intercepts against projected threats would be over homeland territory. This brings with it the problems of collateral damage and in most cases a restricted opportunity for "shoot-look-shoot" firing doctrine.This gives rise to the operational use of the System Concepts examined by NIAG SG-37 in

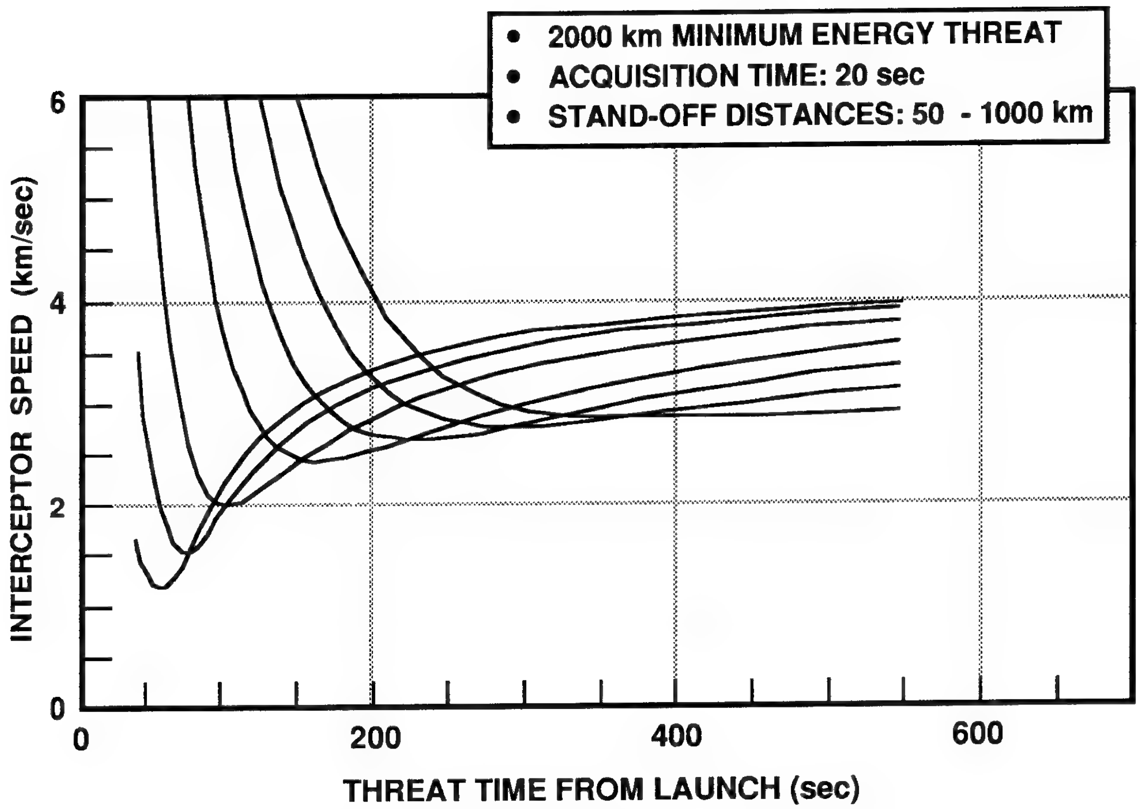

Figure 2-11: Interceptor Speeds Required to Intercept a TBM

boost phase operations. Figure 2-11 shows the results of some of the work where an examination was made of how fast an interceptor would have to be to intercept a given missile at various stand-off distances from the attacking missile launch point.

The particular set of calculations shown in Figure 2-11 were done for a ship based system at stand-off distances from 50km to 1000km from the launch point. The lowest curve in Figure 2-11 is for 50km; the highest curve is for 1000km. Making reasonable allowances for aerodynamic drag, the data shown can also be used to first approximation for aircraft launched interceptors. It is recalled that the boost time for a 2000km range threat is of the order of 85 seconds. From Figure 2-11 this shows that for boost phase intercept, high speed interceptors are required for distances greater than say 500km.

If cueing and mid-course correction is possible then greater distances can be tolerated. Shipborne systems would have to move closer in and airborne systems would have to be vectored over enemy territory with today's interceptor systems. These operational considerations show that under controlled conditions it is possible to intercept in the boost phase and contribute against chemical warhead and other attacks.

Shipborne Operations

In earlier sections, it was shown that the use of shipborne operations offers several significant advantages for a NATO wide EAD system. The advantages of forward basing of interceptors and sensors (radars) have been demonstrated. The flexibility of siting is important because of the inherent cost of fixed ground based systems and the transportability issues of all forms of interceptor systems.

A political factor not examined, is the "non-threatening" nature of a ship based system when shared amongst nations and the ability to indicate strength of will to an intending attacker as the ship based defence system "steams" toward the attacker allowing him time to reconsider.

Ref 2 shows how eight (8) ships positioned around Europe could protect against long range missile threats coming from Iraq. If long range threats greater than say 3000-5000km do not materialize

then the ships could be reduced to four (4) in the Mediterranean and lower the cost. This is a matter of threat assessment and timing. In Ref 2, this concept is expanded upon further by showing that if the threat axis moves to Libya, a minor repositioning of the same ships can provide the same degree of protection. The ship movement can be accomplished within a days's "steaming".

By installing the interceptor and radar on ships (and not necessarily the same ship) provides several advantages for EAD. First, like the airborne interceptor discussed above, ships can be on station in the threat area and because they are now forward based, significant improvements can be obtained in the size of the protected footprint . Specific examples of this shipborne concept are provided in Ref 2.

From a political viewpoint, the use of shipborne interceptors can assuage fears of individual nations building missile sites around their borders with the intention of launching interceptors into the airspace over neighbouring nations headed toward some hostile nation. Further, because of the uncertainty of the threat direction in the coming decades, the use of shipborne assets greatly facilitates moving the interceptor "sites" to more advantageous locations thus avoiding a modern day "Maginot Line". It is believed that if such ships were part of a NATO command structure then the multi-national sharing of the defence burden can be significantly lessened.

Cueing and Handover

Significant improvements in protected footprints can be achieved if the defending radar can be cued by a forward based sensor. This sensor could be an IR satellite or a forward based aircraft (such as described in System Concept 103). This improvement comes about through the ability of the defending radar to increase its range by focussing the beam in a known direction (through cueing) rather than being required to continuously sweep large volumes, searching for the incoming missile. A similar situation applies to the cruise missile. An alternative approach is to make use of forward based radars which then "handover" the target information to the defending radar. The choice between cueing and handover is a matter of cost and performance trade for particular scenarios.

Airborne Operations

Inherent in the Aircraft Based Interceptor (SC 111) among other attributes, is the ability to intercept TBM during the boost phase. Because of the short timelines (see Section 4.0) it is difficult for defensive systems located on "home soil" to first detect the launch and track boost phase flight, and secondly, virtually impossible to intercept during boost phase. During CRISIS and WAR operations, the airborne interceptor can be on station and accomplish boost phase intercepts. The kinematics of this possibility is similar to the shipborne case shown in Figure 2-11, except that now there are no sea-land boundary constraints.

Strategic Positioning

A major concern for defence against long range TBM is that the battle space will reach beyond national boundaries and that the debris of intercepts may fall on neighbouring nations (friendly or otherwise). Such events can clearly complicate the defence and incur serious consequences of "friendly fire". By strategically positioning the interceptor and radar sites around NATO, it can be shown that it is possible to cause debris to fall into uninhabited regions or in the sea. As a political tool, it is also possible when intercepting in the boost phase to cause the debris to fall back on the attacker. This might have a dissuasion effect especially if the attacking missile contains chemical or nuclear waste material. More details of possible strategic positioning is given in Ref 2.

An example of how such placement of defence assets might be used for this purpose is shown in Figure 2-12 for two cases of interceptor speeds (Vbo=3km/sec and Vbo=6km/sec). While not discussed in Ref 2, it can be seen from Figure 2-12 that not only does such placement help NATO defend against a threat from the Southern Region, it serves to protect the FSU from the same threat, suggesting some benefit for future alliances.

For such long ranges, it is now possible to "use" the geography of the globe to advantage. For the case of Vbo=3km/sec, the interceptor debris (not burnt up upon reentry) is seen to land in the Mediterranean. For the case of Vbo=6km/sec, the interceptor debris can be directed by delayed launch of the interceptor, and caused to land in the Atlantic Ocean. These are illustrative cases only, and more detailed analyses, taking into account all of the parameters discussed in this report need to be taken into consideration for final evaluation. But the principles as stated here are correct.

It will be noticed from plots such as Figure 2-12, that it is possible to position the interceptor site such that the debris can be directed back to the attacker!

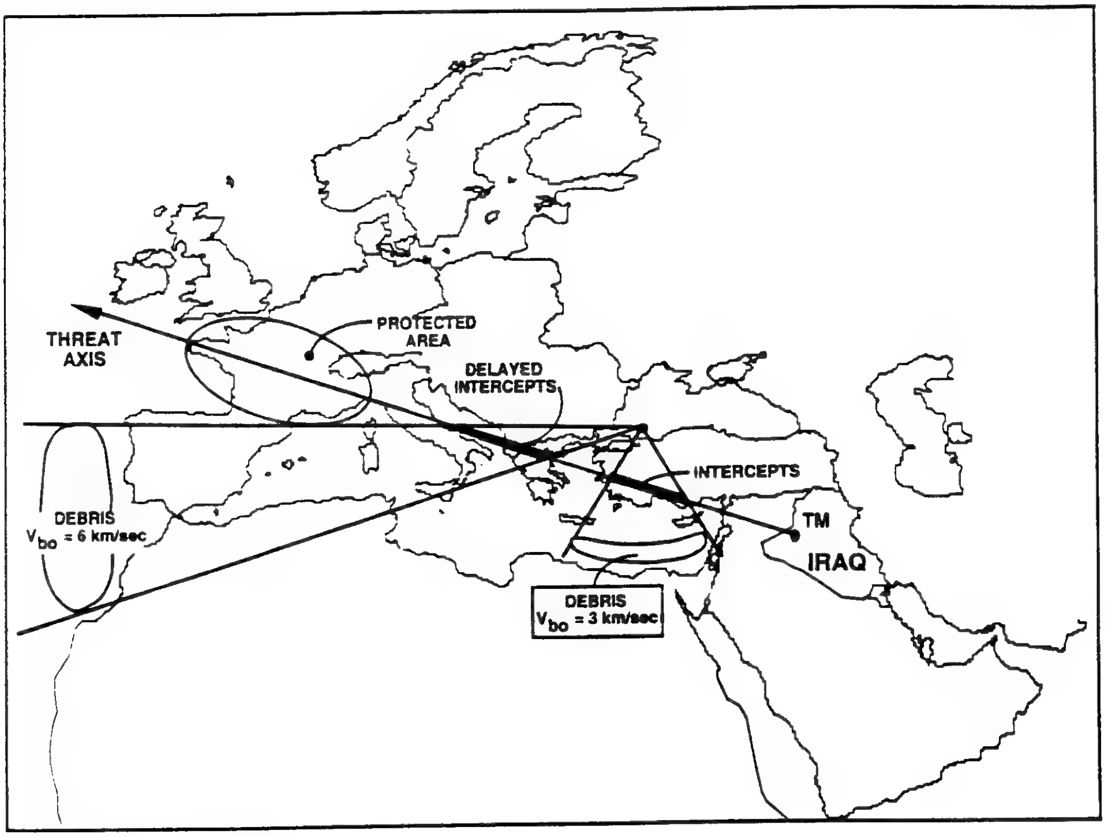

Figure 2-12: Strategic Positioning to Minimize Collateral Damage

CONCLUDING REMARKS

This paper has covered some of the key findings by NIAG SG-37 during a one year activity exploring the issues and solutions to the general topic of providing Extended Air Defence capability for NATO and it's Out of Area Forces. The full report (Ref 2) contains more detailed information including the Evaluation Methodology, the Costing Methods and detailed technical data on many of the technology issues only briefly referred to in this overview paper.

Out of this work has come recognition of the need to approach Extended Air Defence in a Multi-Layer Defence system made up of various combinations of space based assets, aircraft, missiles and other assets. NIAG SG-37 is embarking on this task in 1994 under its MLD-2000 tasking.

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2. "Extended Air Defence Post 2000 (EAD-2000)", NIAG Report: AC/224 (AG VI)-D/13, NIAG-D(93)13, three volumes, dated October 1993

DEFINITION D'UNE ARCHITECTURE DE DEFENSE ANTI-MISSILE BALISTIQUE POUR L'EUROPE

M. DEAS
Directeur Commercial
A. TANTER
Directeur des Programmes
G.I.E. COSYDE
4, Avenue Morane Saulnier
78140 Vélizy-Villacoublay
France

1. Introduction

La fin des années 70 et le début des années 80 ont vu des développements technologiques importants pour les missiles balistiques notamment en ce qui concerne la précision à l'impact. Ces améliorations ont conduit les stratèges occidentaux à se préoccuper de l'utilisation par le Pacte de Varsovie de missiles balistiques équipés de charges conventionnelles contre des objectifs militaires. La notion de missile balistique tactique était née.

Le vecteur balistique, qui était jusqu'à cette époque marqué d'une étiquette "stratégique", s'est alors "banalisé" et a intéressé nombre de pays en voie de développement. Le monde venait d'entrer dans l'ère de la prolifération balistique.

Dès le début des années 80, les Etats-Unis et, à un degré moindre, l'OTAN conduisaient des études et des réflexions concernant la défense contre les missiles balistiques tactiques dans un cadre Est-Ouest : l'"ATBM" (Anti Tactical Ballistic Missile) faisait son apparition. Malgré les tentatives de contrôle la prolifération s'accélérait et conduisait vers la fin des années 80/début des années 90 à la prise de conscience d'un nouveau risque dit proliférant.

La Guerre du Golfe en 1991 accélérait de la manière que l'on sait, cette prise de conscience. Ce conflit mettait également en lumière le fait que l'arme balistique constituait un moyen de pression formidable pour les pays qui en disposaient et ce, malgré les PATRIOT qui faisaient la démonstration de la faisabilité d'une défense active contre missiles balistiques malgré les limitations de leurs performances.

La présente présentation se propose d'analyser globalement le risque balistique et la menace éventuelle qui pourrait en résulter, d'examiner l'ensemble des moyens disponibles pour la protection contre ce risque en approfondissant tous les moyens défensifs qui constitueront l'essentiel du discours. Enfin, en guise de conclusions, elle s'efforcera d'évaluer les difficultés auxquelles les architectes de la DAMB devront faire face.

2. Le risque balistique

En terme de risque il ne faut pas oublier que des missiles stratégiques intercontinentaux (portée supérieure à 5500 km) sont toujours déployés dans les 4 "grandes républiques de la CEI". Les modifications géostratégiques récentes ont cependant diminué considérablement la probabilité d'une confrontation Est-Ouest. L'accord FNI de 1987 a élimine la menace 500 à 5500 km. Il reste néanmoins un inventaire important de missiles de portée inférieure à 500 km dans les pays de la CEI.Il s'agit de FROG (70 km), SS21 (120 km) et SCUD (300 km). Ces missiles sont dotés de charges conventionnelles, chimiques et nucléaires.

Trois républiques de la CEI ont la capacité technique d'améliorer ces missiles en leur donnant une grande précision. Ceci leur ouvre la possibilité d'attaques efficaces d'objectifs militaires avec des charges conventionnelles. Les autres républiques seront traitées comme des pays proliférants.

La prolifération, se présente de deux façons différentes :

C'est d'abord l'achat "clés en main" de systèmes qui seront opérationnels peu après leur livraison, FROG, SS21 et SCUD fournisdans le passé par l'URSS, aujourd'hui par la Corée du Nord et par la Chine. Cette dernière ne se limite pas à l'exportation de missiles courte portée comme le montre la fourniture de CSS2 (2700 km) à l'Arabie Saoudite.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

La deuxième démarche consiste à développer des programmes propres de missiles balistiques. Cette démarche peut être plus ou moins élaborée, allant de l'assemblage de missiles reçus en pièces détachées au développement national, favorisé par la diffusion des technologies et du savoir-faire, en passant par des modifications ou copies.

La menace présente comprend pour l'essentiel des missiles de portées inférieures à 1000 km équipés de charges conventionnelles. L'apparition de charges chimiques sur ces missiles parait possible à court terme. Cet arsenal constitue un risque pour les pays du flanc sud de l'Europe.

Techniquement il est possible que, dès 2005, de nouveaux pays se dotent de missiles de portée supérieure à 3000 km. La totalité de l'Europe serait alors menacée.

Ce risque pourrait être considérablement augmenté si ces missiles emportaient des charges nucléaires. En dehors de l'achat, favorisé par le retrait du service opérationnel de nombreuses charges nucléaires par la CEI en application des traités, des charges nucléaires pour missile balistique pourraient être développées par des pays proliférants dès 2005.

La précision obtenue de centrales de navigation d'avion, disponibles sur le marché, ne permet pas à des missiles à charges conventionnelles d'avoir une réelle efficacité sur des objectifs militaires. Cette précision est par contre suffisante pour l'attaque, avec des armes de destruction massive, d'objectifs étendus tels que concentrations urbaines.
L'approvisionnement de centrales plus précises ou de récepteurs NAVSTAR apparaît comme le risque le plus plausible d'ici 2005.

Ces missiles proliférants sont considérés comme rustiques dans la mesure où leurs signatures sont relativement importantes, ils ne sont pas ou peu manoeuvrants et ne font pas appel à des aides sophistiquées à la pénétration. L'exemple du AL Hussein qui se brisait en rentrant dans l'atmosphère, illustre bien en quoi ces manoeuvres et aides, bien qu'involontaires, compliquent sérieusement la tâche de la défense.

3. Les moyens de protection

Le risque balistique qui était cantonné à l'Est est maintenant étendu au Sud de l'Europe. La menace peut frapper de manière totalement imprévisible.

Les moyens de protection peuvent se classer en trois grandes catégories : les moyens préventifs politiques et diplomatiques, les moyens militaires offensifs et les moyens militaires défensifs.

Les moyens politiques et diplomatiques sont tous ceux qui tendent à faire baisser le niveau de tension dans le monde à travers des négociations particulières ou la signature d'accords internationaux. On peut citer les accords sur la sécurité en Europe (CSCE) ou le désarmement (CFE), le traité de non prolifération nucléaire ou celui sur les armes chimiques.

Dans le domaine plus spécifique des missiles balistiques, il faut mentionner l'accord MTCR (Missile Technology Control Regime) qui a pour but de contrôler la prolifération des technologies balistiques.

Les moyens militaires offensifs peuvent être utilisés avant le conflit à titre préventif ou bien après le début des hostilités. Les moyens préventifs concernent surtout des attaques préventives sur les installations militaires, ou industrielles voire les leaders politiques (tel le raid américain sur la Libye en 1986). Les mêmes moyens utilisés après le début des hostilités pourraient s'attaquer aux lanceurs de missiles balistiques, il s'agit alors de contre-batterie, ou viser tout autre objectif en représailles. Dans tous les cas, ils nécessitent la mise en oeuvre de systèmes d'armes sophistiqués tant au plan des senseurs que des armes elles-mêmes.

Les moyens militaires défensifs peuvent être soit de nature passive, soit active. Ils ont pour but de protéger le théâtre ou les zones contre la menace balistique. Ils font l'objet d'une description plus détaillée dans le reste de l'article.

Tous ces moyens sont complémentaires ; aucun ne peut garantir à lui seul une assurance de protection suffisante.
L'expérience actuelle montre que la diplomatie a ses limites, même quand elle s'appuye sur des moyens militaires puissants mis en oeuvre dans le cadre d'organisations internationales.
Les moyens défensifs sont pour l'instant inexistants à l'exception des améliorations du

PATRIOT en cours de développement mais dont les capacités resteront limitées face à la menace longue portée.

4. Les moyens défensifs

Il n'est pas dans l'objet de cette présentation de se livrer à une analyse détaillée de la défense passive, même si le problème de la protection des habitants d'une tour de bureaux de 40 étages, avec un préavis inférieur au quart d'heure, mérite réflexion approfondie. La mise en oeuvre de la défense passive nécessitera l'utilisation d'information d'alerte qui seront fournie par un système similaire à un système d'alerte pour défense active décrit dans cet article.

Les missions de défense

Avant de s'intéresser à la description des différents segments d'une défense antimissile balistique, il convient de considérer les missions d'une telle défense. En premier lieu, il faut indiquer ce que cette défense ne fera pas : arrêter une attaque massive synchronisée de missiles sophistiqués et de longue portée. Une telle attaque appelle une riposte de la force de dissuasion nucléaire qui reste le fondement de la doctrine de défense française.

Pour rester crédible, la force de dissuasion ne doit pas pouvoir donner l'impression d'être activée sur une simple provocation représentée par un ou deux missiles balistiques lancés sur le territoire européen. La DAMB est donc destinée à fournir une protection contre les attaques limitées d'une menace rustique, au moins quand elle est à longue portée.

Trois missions peuvent être identifiées :

- protection d'objectifs militaires contre une menace courte portée éventuellement sophistiquée,

- protection de forces d'intervention déployée sur un théâtre d'opérations extérieur et protection des populations amies,

- protection des populations sur le territoire européen contre une attaque limitée mettant en oeuvre des missiles rustiques quelle que soit la portée.

La première mission est proche des missions imaginées par l'OTAN lors d'une attaque du Pacte de Varsovie à la différence près que ce seraient les pays de l'ex-Pacte qui seraient attaqués par les pays de l'ex-URSS.

La deuxième mission correspond complètement au scénario de la Guerre du Golfe.

La troisième mission est nouvelle et diffère des précédentes en ce qu'elle concerne principalement les populations civiles donc la protection de vastes territoires tels que l'Europe.

Les architectures

La conception et la mise en oeuvre des défenses contre missiles balistiques se font à travers des architectures que l'on pourrait également qualifier de systèmes de systèmes.

Une architecture de défense comprend, si l'on excepte les moyens de défense passive, trois grands segments (que les Américains appellent "piliers") eux-mêmes constitués de "briques". Le segment alerte constitué d'un système satellitaire et de radars longue portée, le segment interception constitué d'un certain nombre de systèmes d'interception opérant dans des tranches d'altitudes différentes, enfin, le Système d'Information et de Communications (SIC) constituant l'ossature sur laquelle repose tout l'édifice.

Le Système d'alerte

Les fonctions principales d'un système d'alerte sont de prévenir d'une attaque mais également de déterminer le point de lancement pour aider à l'identification de l'agresseur, estimer le point d'impact avec une précision de quelques dizaines de kilomètres et donner un préavis compatible des durées de vols extrêmement brèves des missiles balistiques.

La détection d'un lancement peut se faire grâce à un ou deux satellites géostationnaires fonctionnant en stéréoscopie, ou grâce à un grand radar basé au sol. Ces radars peuvent être soit des radars dalle à balayage électronique, soit des radars en réseaux.

Le satellite géostationnaire est à même de fournir avec une précision suffisante la détermination du point de lancement, par contre, il lui est difficile d'avoir une bonne précision pour le point d'impact étant donné

que la détection ne s'effectue que pendant la phase propulsée des missiles. Les radars qui continuent la détection pendant la phase balistique sont nécessaires pour une bonne trajectographie.

Une précision équivalente pourrait être obtenue en utilisant une constellation de satellites défilants (de type Brilliant Eyes américain). Les premières analyses montrent cependant qu'à moins de percées technologiques importantes permettant de diminuer les coûts de plusieurs ordres de grandeur, une telle solution n'est pas économiquement viable pour la protection de l'Europe.

Compte tenu des missions spécifiques aux théâtres extérieurs, l'alerte dans ce cas-là peut être fournie par des radars déployables avec les forces d'intervention.

Accessoirement, le système d'alerte déployé participera à la fonction renseignement permettant de nourrir les bases de connaissances utilisées pour l'identification des missiles voire des agresseurs.

Les système d'interception

Les systèmes basse altitude doivent faire face au problème de la menace multiple. En effet, dans la tranche d'altitude 0 à 20 km "cohabitent" les menaces balistiques et aérobies (avions, hélicoptères, missiles de croisière et/ou antiradiations). Un des problèmes qui en résulte concerne la mise au point de systèmes polyvalents. Ceci a un impact sur la conception des radars et des autodirecteurs (accroissement de portée nécessaire pour la menace balistique), des charges de combat (nombreux petits éclats à grande vitesse contre la menace aérobie opposés à moins d'éclats plus gros à plus faible vitesse contre la menace balistique) et des fusées de proximité (angle d'approche différent compte tenu des vitesses de rapprochement).

Les systèmes les plus connus dans cette catégorie sont le PATRIOT utilisé pendant la Guerre du Golfe et le système SAMPT développé en coopération par la France et l'Italie au sein du GIE EUROSAM.

L'interception à haute altitude, voire exoatmosphérique est nécessaire pour permettre de défendre de larges zones. De plus elle comporte l'avantage de réduire les retombées des débris du missile assaillant. Ceci est d'autant plus intéressant que les charges peuvent être chimiques voire nucléaires.

Pour être efficaces les intercepteurs haute altitude ont des vitesses d'injection comprises, suivant les concepts, entre 2500 et 5000 m/s la charge utile est de masse faible et constituée d'un autodirecteur infrarouge et d'un véhicule terminal léger à propulsion latérale. Ce véhicule terminal repose sur le principe de destruction à l'impact direct ("hit to kill" en anglais). Il n'est alors plus question d'éclats générés par une charge de combat volumineuse mais de tout moyen permettant au moment de l'impact de réduire la distance de passage et d'augmenter le maître-couple de l'intercepteur. Les Américains dans l'expérience HOE (High Overlay Experiment) ont utilisé le principe des baleines de parapluies, un des concepts utilisés dans l'ERIS serait constitué de masselottes collées sur un ballon en mylar gonflé peu avant l'impact.

Lors d'une interception exoatmosphérique (altitude supérieure à 100 km) un des problèmes à résoudre sera celui de la discrimination de la charge à détruire au milieu du cortège constitué par un certain nombre d'objets, tels que sangles, coiffes, boulons voire de leurres.

C'est en phase propulsée que le missile assaillant est le plus vulnérable. Il faut cependant pouvoir le détecter et l'intercepter suffisamment tôt. Quand les conditions géographiques s'y prêtent, et c'est le cas en Méditerrannée, une composante navale de la Défense Anti-Missile Balistique présente un grand intérêt. Si l'on ajoute les avantages liés à la taille des zônes protégées, l'interception au-dessus du territoire de l'agresseur qui présente un intérêt évident dans le cas d'armes de destruction massive (chimique ou nucléaire) ou de têtes multiples, la mobilité, la non désignation a priori de l'agresseur, l'utilisation en eaux internationales et près du territoire à protéger il ne faut pas s'étonner de l'attention grandissante portée à cette composante. La Marine américaine qui s'engage dans la modification du système d'arme AEGIS montre encore ici la voie.

L'interception en phase de propulsion ou ascendante peut également s'envisager à partir

de systèmes aéroportés avions ou drones. La faisabilité technique et l'intérêt opérationnel pour la protection du territoire européen restent à démontrer.

Les Systèmes d'Informations et de Communication (SIC)

Les segments alerte et interception ne pourront pas fonctionner correctement, ni remplir leurs missions s'ils ne sont pas connectés avec et par un ou des SIC. Le conflit "balistique" auquel nous nous intéressons est limité, c'est-à-dire mettant en oeuvre des missiles assaillants dont la quantité et la complexité ne conduisent pas au traitement d'une masse d'informations prohibitive en matière de puissance de calcul. Par contre l'autre caractéristique de la menace balistique est le faible temps de vol et de préavis qui exclut pratiquement l'intervention de l'homme dans la boucle de décision d'engagement (sauf peut-être pour imposer un veto). L'automatisation des procédures qui en résulte nécessitera des mises au point extrêmement délicates.

L'internationalisation du problème signifie que le SIC DAMB aura des interfaces nombreux avec des SIC existants ou en cours de développements en Europe y compris centrale et orientale.

Qui dit multinational, dit concertation, respect de l'indépendance de chaque pays participant, notions qui sont difficilement conciliables avec les problèmes de temps de réaction et d'absence d'homme dans la boucle.

5. Constructions d'architecture et aspect multinational

Si l'on considère l'état actuel du déploiement des missiles balistiques dans le monde, on s'aperçoit que les missiles les plus répandus sont ceux de portée inférieure à 500 km. Ces missiles sont généralement mono étage, de surface équivalente radar importante et de vitesse de rentrée voisine de 1700 m/s.

Il est possible d'envisager l'interception de tels missiles dans leur phase finale de trajectoire avec des systèmes d'interception bas endoatmosphérique tels le PATRIOT et le SAMPT déjà mentionnés ou les systèmes en développement moins avancé tels que TLVS et CORPSAM.

Une architecture monocouche basée sur ces systèmes pour faire face à une telle menace est déployable autour de l'an 2000 et est envisageable pour la protection du Sud de l'Europe et sur des théâtres extérieurs. L'architecture complète doit inclure un système d'alerte comportant des radars basés au sol alertés ou non par des satellites.

L'avantage d'une telle architecture outre la possibilité de déplacement rapide réside dans le fait qu'elle peut être pratiquement envisagée comme une architecture nationale. Elle est cependant limitée en performance face à une menace longue portée.

Cette menace longue portée dont un exemple déployé actuellement au Moyen Orient est le missile type CSS2 est caractérisé par une portée proche de 3000 km. Bien que ce ne soit pas le cas du CSS2 elle est en général multi-étage avec un temps de vol voisin de 17 mn et une vitesse de rentrée voisine de 4800 m/s. Outre la difficulté d'interception en phase terminale d'une telle menace la recherche de couverture de larges zones pour protéger les populations et l'intérêt d'intercepter des charges chimiques en très haute altitude, voire hors de l'atmosphère, conduisent à déployer une couche d'interception haute altitude. Cette couche peut elle-même être divisée en deux sous-couches : haut endoatmosphérique et exoatmosphérique.

Dans la catégorie haut endoatmosphérique les systèmes candidats sont le THAAD (Theater High Altitude Area Defense) américain ou l'ARROW israéliens. Dans la catégorie exoatmosphérique les concepts candidats sont américains, il s'agit du GBI (Ground Based Interception) sans oublier les modifications du missile STANDARD pour lui faire emporter le LEAP.

Dans le cas de la protection contre les missiles longue portée les contraintes liées à la détection et l'interception conduiront obligatoirement à internationaliser le problème.

La détection et l'interception d'un missile type CSS2 lancé d'un point situé au Sud de la Méditerrannée contre Bruxelles peuvent donner lieu au scénario fictif ci-après.

T0 Un satellite du système d'alerte détecte le lancement. L'information est relayée au centre satellitaire de TORREJON en Espagne.

T0+1' Après confirmation, l'alerte est transmise au Centre de commandement de DARMSTADT en Allemagne.
Les responsables politiques nationaux sont immédiatement informés et le système de défense antibalistique européen est mis en alerte.

T0+2' Le radar longue portée situé à Bari, (Italie) détecte le missile assaillant et entreprend sa poursuite.
Les informations qu'il transmet au centre de commandement permettent d'identifier le type de missile : CSS2, sa cible : le sud de la Belgique et son heure probable d'impact.

T0+5' L'alerte est donnée sur la zone menacée.

T0+7' Darmstadt précise que l'impact est prévu à Bruxelles à T0+17.

T0+10' Le radar du centre d'interception de Marseille, (France) accroche le missile et commence le pistage.

T0+11' La mise à feu d'un missile intercepteur est automatiquement ordonnée par la conduite de tir.

T0+14' Le missile assaillant est intercepté en haute altitude.

Cet exemple démontre bien le caractère multinational de la défense contre missiles longue portée. Cet aspect est déjà compris dans l'ACCS mais il prend une dimension plus importante quand on envisage la protection de toute l'Europe. Dans ce cas il sera nécessaire d'interconnecter deux mondes qui étaient adversaires il y a peu de temps.

6. Les difficultés

La description des éléments constitutifs de l'architecture n'a jamais fait référence à des problèmes technologiques majeurs. Il n'a été fait qu'une seule fois allusion a des technologies laser et autres faisceaux de particules. L'utilisation de ces technologies ou de technologies dites exotiques telles que les canons électromagnétiques n'est pas nécessaire pour atteindre les performances requises dans le cadre limité de la défense contre missiles balistiques rustiques.

Le fait que les architectures proposées ne fassent appel qu'à des technologies disponibles ou en voie de maturation ne signifie pas pour autant que les problèmes à résoudre, soient simples. Cependant, le nombre limité de paramètres et leur plage étroite de variations permettent de dire qu'il n'y a pas de risque technologique majeur dans le développement des systèmes composant l'architecture.

En revanche les difficultés pourraient apparaître à l'occasion de l'intégration des technologies dans les équipements. Par exemple, il n'a jamais été procédé en Europe à l'intégration d'un satellite géostationnaire optique bien que toutes les technologies existent. L'exemple du satellite DSP américain reposant sur les mêmes principes prouve que cette intégration est possible. De même si les technologies de pilotage en force sont connues, seul les Américains en ont démontré l'intégration et ont effectué une interception non nucléaire d'un missile exoatmosphérique (interception d'un MINUTEMAN par le véhicule ERIS).

D'autres difficultés sont à prévoir pour les essais et évaluation de ces systèmes notamment les systèmes d'interceptions. La définition et l'analyse des performances d'une architecture de défense fera appel à des moyens de simulations regroupés dans des centres ou interconnectés. La bataille complète ne pourra qu'être simulée mais il faudra cependant vérifier sur champ de tirs l'efficacité des intercepteurs sur des cibles représentatives.

Compte tenu de la cinématique des interceptions et des problèmes de sécurité, il semble a priori exclu d'effectuer ce type d'essai en Europe. Mais effectuer de tels essais dans des pays même amis ou sur des champs de tirs dans le Pacifique imposera des contraintes supplémentaires.

Cependant les principales difficultés seront d'ordre politique et opérationnel. Elles se retrouveront principalement dans les SIC. Comment concilier les soucis d'indépendance nationale et la coordination multinationale avec un temps de préavis extrêmement court ? Comment garantir le libre accès à l'information tout en protégeant ses propres sources ? La duplication des réseaux SIC sera certainement un écueil qui ne sera pas facile à éviter.

7. Conclusion

La Défense antimissile Balistique est accessible technologiquement et techniquement. Il ne semble pas pour l'instant qu'il y ait des problèmes technologiques critiques.

Ceci s'entend pour une architecture DAMB contre une attaque limitée telle que décrite sommairement dans ces pages. L'analyse des missions proposées sera à faire de manière détaillée voire contradictoire car toute extension de la mission vers des missiles plus sophistiqués ou des scénarios d'attaque plus élaborés aura un impact important sur les performances des systèmes et surtout les quantités déployées donc le coût.

La définition des missions étant du ressort des responsables politiques, il est évident que la majorité des problèmes sera d'ordre politique. La mise en oeuvre d'une défense des populations civiles à travers des équipements déployés ou sous contrôle d'un autre pays risque de poser de graves problèmes. Il sera nécessaire de procéder à une étroite coopération internationale pour la définition des architectures de défense mais également, leur mise en oeuvre. Vu l'ampleur de la tâche, il est souhaitable que cette coopération s'engage dès à présent.

Possible Allied Ballistic Missile Defense Systems, related guidance and control requirements

C. ROCHE, C. COTILLARD

MATRA DEFENSE ESPACE
37, Avenue Louis Bréguet - B.P. 1
78146 Vélizy Villacoublay Cedex
France

1. TWO TYPES OF THREATS

Different scenario can be build up for NATO forces showing deployment and use of anti ballistic missiles defenses.

Most of these scenarii imply open crisis, and complex mix of attack, retaliation and deterrence actions. The description of these could evidently lead to unnecessary sensitivity about the probability of such or such hostile nation being implied, or about the credibility of such and such deterrence. Nevertheless some ideas or principles can be raised and presented.

Two main types of ballistic attacks appear : medium range and long range attacks :

- Medium range attacks use missiles with ranges up to 1000 km. They can be Scud, modified Scuds, Nodong's, chinese M's. They show the greatest number and also the greatest increase of number in the non NATO countries.

  They can be used according to their ranges either from one country to another, when they are close, or from one country to deployed close by forces in a military engagement. The launching areas would have sizes around 500 km, the aimed at areas would have also sizes around 500 km. The goals of these attacks can either be strategic or tactic. And the results can be fear / panic and deads in the civil population, as well as deads and operational inefficiency amongst troops and defense means.

  Geographically this can occur on some flanks of European Nato countries, and mainly in out of area theater operations.

- Long range attacks use missile which ranges higher than 1000 km. They can be chinese CSS's or russian SS's. They are much less proliferating that the others, but from many possible countries they can reach all European Nato countries, with much bigger strategical impacts and deterrence capacities.

  They can be launched from all parts of hostile countries, that is most of the time below 2000 km size zones per country, the possible aimed at area can be the whole of Europe.

  Outside few scenarios that look like cold war scenarios and that lead to be handled the same way, the attacks would be with less number of ammunitions and launches that the medium range case, but with bigger probability of mass destruction warheads.

  Also less probability occurs of their use in theater attacks against troops.

  In both, medium and long range attacks cases, the possible hostile means are with rustic warheads, with no decoys or a minimum of decoys. After a more or less long period of time, decoys and Mirv's could appear. They more likely will appear first in the long range threats, for two important reasons :

1 Long range systems leads to the more expensive investment from the hostile, with the bigger strategical / political value of the success of a strike.

2 This is the case where the antimissile defenses have the smaller efficiency against the decoys (cf after).

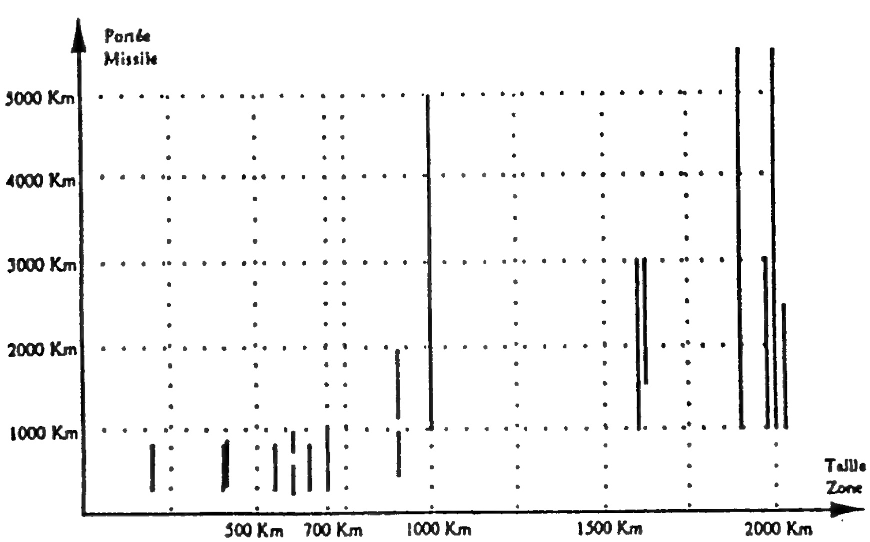


Fig. 1 - Statistics of ranges of hostile missiles, against size of launching zone

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

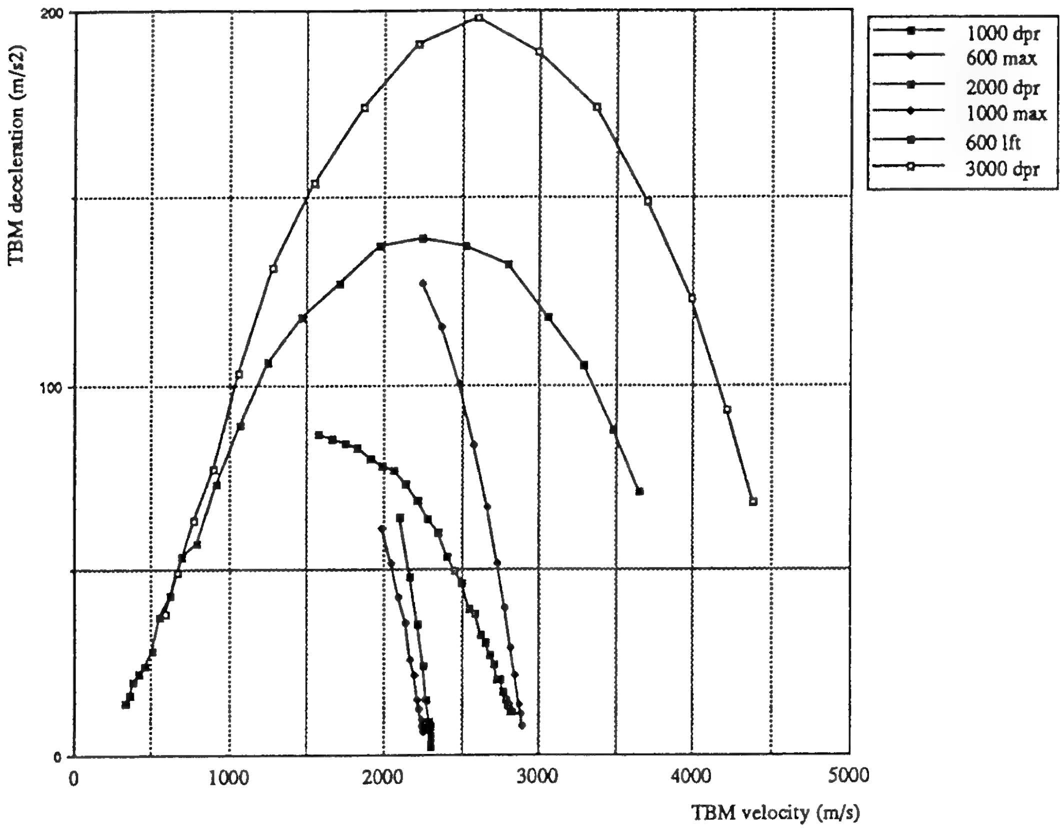


Fig. 2 - TBM's velocity and deceleration characteristics in the 5 - 25 km altitude domain

2. THREE TYPES OF INTERCEPTORS

Against these types of attacks, anti ballistic interceptors can also be divided into categories :

- Medium / Long range air defense missiles with extended capabilities or upgraded versions to intercept ballistic missiles. As exemple we find US Patriot's and SM2 BLK IV, russian S 300 V, european SAMP/T systems.

- Endo / exo ATBM's which have no capabilities against air breathing threats but are able to intercept ballistic missiles in the upper range of the atmosphere and also in exo atmospheric conditions. The typical and only example is the American Thaad, under advanced development.

- Pure exo intercept system with only exo atmospheric intercept capabilities, they can be ship launched or air launched, with different operational conditions, and different technical interests. The typical systems are LEAP based, for instance US SM2 + LEAP, or UK Gllees.

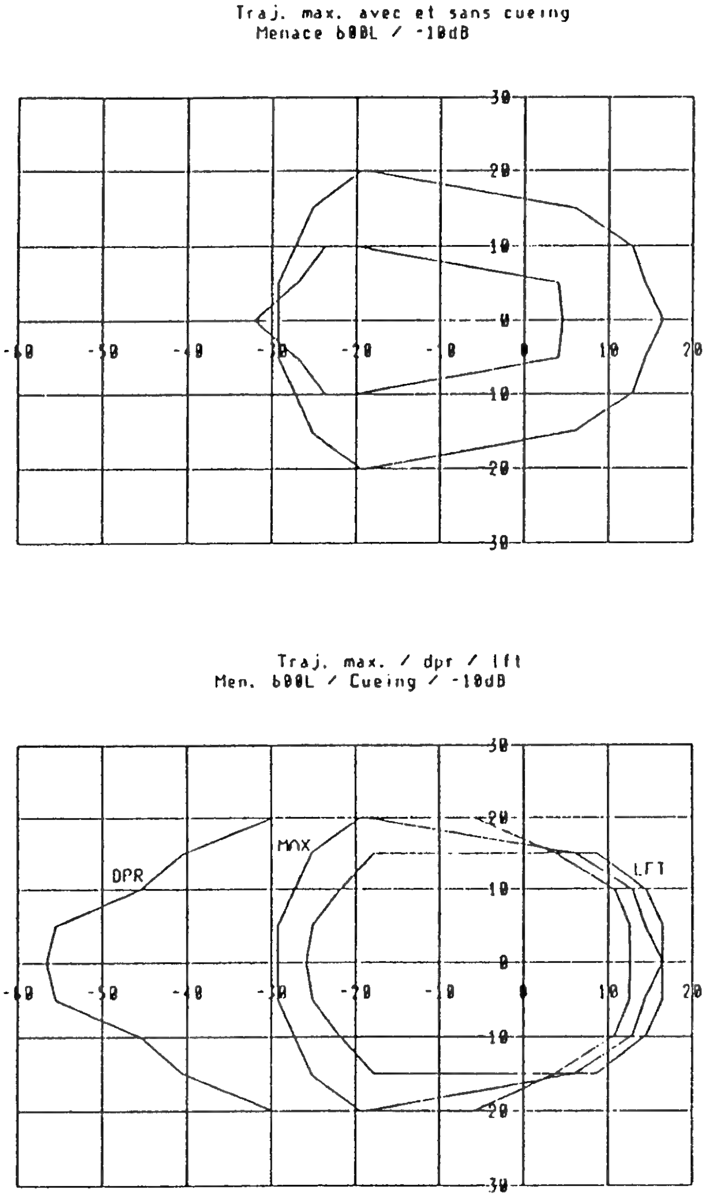


Fig. 3 - Endo system footprint example

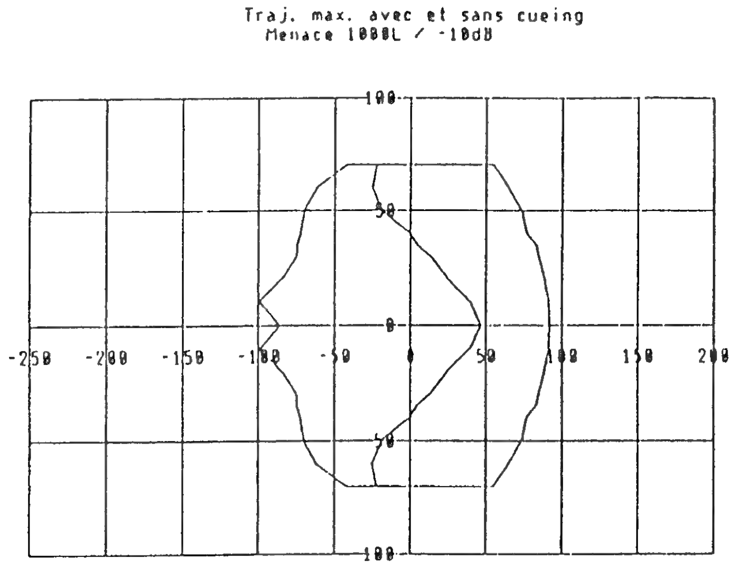
2.1 MSAM with ATBM capabilities

Air defense missile systems with ATBM capabilities will intercept TBM's under 20-25 km altitude. They are equipped with RF seeker, IR being not suitable for all-weather operations. In this region of the atmosphere, the ballistic target will suffer aerodynamic deceleration and may even maneuver. The range of TBM velocity and deceleration is wide when going from short range TBM (range less than 1000 km) to long range TBM and this also depends on the type of trajectory (minimum energy, lofted and depressed). Based on these considerations, hit to kill is very difficult to achieve, therefore heavy warheads (large fragment size to ensure sufficent kill probability levels) is often required to ensure sufficient kill probability levels. Taking into account the high target velocities and possible low signatures, the time dedicated to engagement sequence is short and therefore high average interceptor velocity together with extended radar range are required. Radar cueing is one of the most important point in order to enhance footprint size, this means that detection and pre-designation systems such as satellite and/or long range radars are required for an effective TBM's defense.

Such systems with dual capabilities (airbreathing targets and TBM's) will have sufficient performance against short range TBM's (less than 1000 km) but will be limited against longer range missiles (missile and radar limitations).

The laws of guidance and optimization of warhead killing lead to a front end attack inside a rather small angle cone. This together with the range and altitude of the kill lead to a footprint (that is the protected zone per battery) with a size of about 100 to 1000 km^2 and approximately centered at the location of the defense battery.

The efficiency of these MSAM's against most of decoys are rather good, as the latter are considerably slowed down entering the atmosphere. Heavy decoys and MIRV's can have to be handled by coordinated multishots, using several batteries, discriminating radars and seeker coordination.



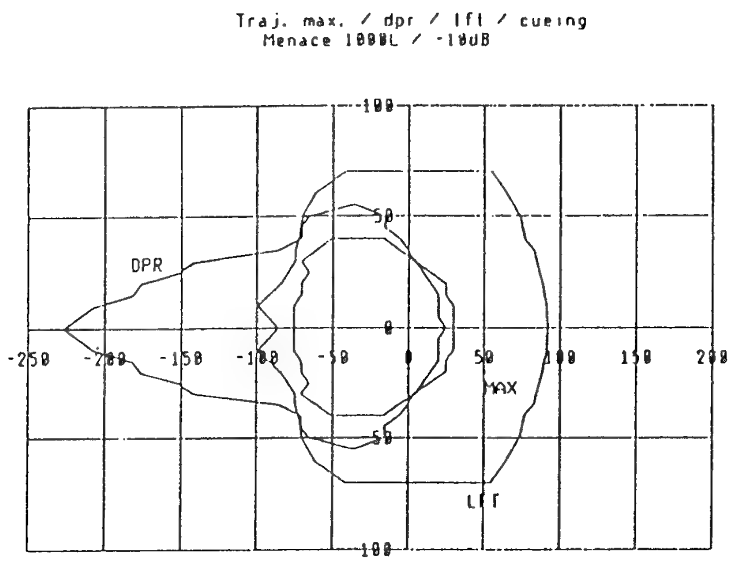


Fig. 4 - Endo exo system footprint example

2.2 Endo-exo systems

Endo-exo systems will intercept TBM's between 50 to 160 km altitude. They require longer range acquisition radars (500 to 1000 km detection range on TBM's) in order to fully use the possibilities of intercept vehicles. The kill vehicle is equipped with both aerodynamic and thrust control in order to achieve endo and exo-atmospheric intercepts. Hit to kill (with possible enhanced lethality radius) is achieved by using infrared guidance technics. As the kill vehicle must operate in endo and exo conditions, kinetic heating will require IR window cooling for endo operations. Therefore, the endo-exo kill vehicle will be heavier than a pure exo kill vehicle.

The laws of guidance and optimization of warhead killing preferably lead to a front end attack inside angle cone smaller when the intercept is lower in atmosphere. These lead to a footprint ranging from 20000 to 1000000 km^2 depending on the cueing and the range of the hostile missile. They are also approximately centered at the location of the defense battery. The efficiency of these endo-exo systems is good against light decoys. They have to be handled by more complex coordinated multishots, discriminating radars and seeker coordination.

2.3 Exo systems

Exo atmospheric kill vehicle requires the same basic elements as endo-exo kill vehicle, but the exo kill vehicle will have to operate without atmospheric heating. On the other hand, against proliferating threats which may deploy even light decoys, discrimination will be one of the critical point for the kill vehicle. The exo kill vehicle requires also very long range acquisition and fire control systems in order to fully use the kill vehicle capabilities and give large footprint sizes. If range of the sensor is such that it is not a constraint like in Brilliant Eyes, footprints could reach 3000 km in diameter. If radar is used and well placed footprint could be 100 km wide. In any case, the battery has to be forward based, almost at the fringe of the protected zone.

3. THREE TYPES OF ARCHITECTURES

3.1 Defense architecture against medium range attack

The medium range attacks are such that the missile often do not fly enough time in space, and time of impact is to short, to efficiently use pure exo atmospheric systems. But if the ranges of the attack is above 300 / 500 km, they have technical efficiency. The ATBM battery with the very long range radar has to be forward based at the fringe of the zone to be protected towards the hostile. This has to be operationnally managed, given the battery can be ship borne or ground based. The footprint of this defense is such that a theater with size up to 1000 x 500 km can be protected by one only battery.

The endo / exo systems have also good efficiency and a theater with size up to 1000 x 500 km could be protected by 2 to 3 batteries, if their powerful mobile GBR radars are cued by early warning satellite. When no cue is performed, about ten times more batteries should be necessary.

The endo systems have also good efficiency, but as they are lighter and more mobile, they have smaller footprints and protect only 100 to 1000 km^2 : the fact that their radar is cued or not has also a great importance.

The cue can be done in that case either by satellite or by GBR's.

Hence the medium range attacks could be handled by a two layers defense using both endosystems and endoexo or exo systems. In that case endosystems should be used for doubling the protection of more sensitive points like air bases, headquarters, telecommunication nodes and the endo / exo batteries themselves or exo. The less sensitive part of the theater zone would then be protected by only one layer exo / endo or exo system only.

In some cases, where possible, picket radars could enhance the cueing of the battery radars. They have then to be forward based. The easiest mean is ship borne radars, but sea has to exist and air and sea superiority have to be achieved. Picket ship radars have also to be cued in order to handle these missions : if not, 800 km to 1000 km missiles launched from far inside the hostile country could pass over the efficiency volume of the radar.

In the next 20 years these types of attack seems likely to have rustic warhead maybe light decoys but not heavy decoys and MIRV's. In these cases the presented defense architecture is efficient.

3.2 Defense architecture against long range rustic attack

If attack range is bigger than 1000 km, most of the endoatmospheric systems seems likely to have smaller efficiency with shorter footprints and smaller probability of kill.

Altogether this type of attacks is such that the warhead should be powerful and the sensitive "points" to be protected are much bigger than the latter case : they should be towns, industrial complexes, defense complexes,..

Then the adapted defense seems again to be a two layer defense with :

- an endo / exo system deployment, for the "point" defense
- an exo system which is particularly adapted for large zone defense : with 2 or 3 batteries which could be ship based according to the direction of threat, most of Europe can be protected.

This architecture would be very efficient against rustic warheads with rustic decoys that can be easily discriminated in space.

If threat is sophisticated, with MIRV's and heavy decoys, the necessary architecture could be the following :

3.3 Defense architecture against long range attack with important countermeasures

Two defense layers can be deployed in the case of long range attack with countermeasures involving heavy decoys and MIRV's :

- an endo / exo system deployments, for the point defense, with a discriminating radar, and correlating seekers system
- an airborne ascent phase interceptor using exokill capabilities much like exointerceptors of § 2-3 or when technics permit Direct Energy weapons.

Those solutions have still to be studied both technically and operationally.

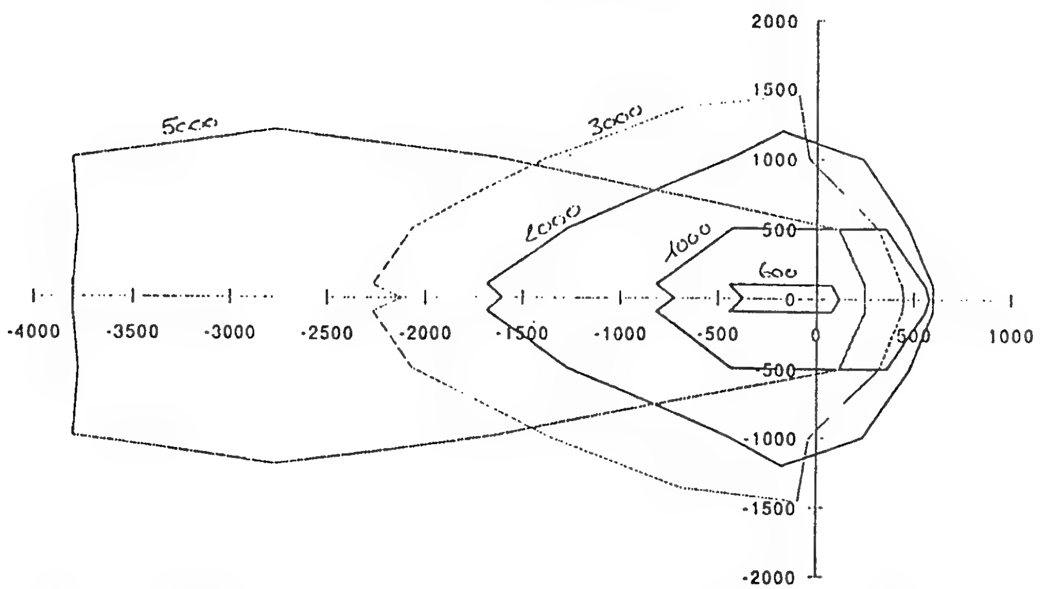


Fig. 5 - Exoatmospheric interceptor footprints example. Radar range 2000 km

SOSIE
Une approche pragmatique de la simulation en défense aérienne élargie appliquée au niveau du théâtre

A. TANTER
Directeur des Programmes
M. DEAS
Directeur Commercial

G.I.E. COSYDE
4, Avenue Morane Saulnier
78140 Vélizy-Villacoublay
France

1. Introduction
Le concept SOSIE repose sur une approche consistant à utiliser au maximum les modèles de simulation existants au niveau des systèmes et sous-systèmes et à les intégrer de manière automatique avec un minimum de modifications au sein d'un centre de simulation.

La simulation de la défense aérienne élargie, qui comprend la défense contre missiles balistiques au niveau du théâtre, fait appel à trois niveaux de simulation.

SOSIE met en oeuvre trois modèles de simulation : DIAMS au niveau le plus fin pour simuler les systèmes d'armes sol-air moyenne portée ; TACSIT au niveau de la défense de site (base aérienne par exemple) et SPOOK au niveau du théâtre.

SOSIE permet à différents types d'utilisateurs d'utiliser les mêmes simulateurs détaillés développés par un concepteur de systèmes d'armes ou d'informations et de communications sans avoir à connaître dans le détail ces modèles de simulation.

Il est prévu dans le futur d'intégrer d'autres modèles de simulations concernant en particulier le combat air-air et les réseaux de commandement, contrôle et communications.

2. Généralités
La Défense Aérienne Elargie (DAE) comprend la défense classique contre la menace aérienne (avions, missiles air-sol, missiles de croisière, ...) et la défense contre les missiles balistiques.

Le missile balistique est caractérisé par un temps de transfert entre le lancement et l'impact (7 mn pour un missile de 600 km de portée, 12 mn pour 2000 km) très court qui stresse la défense, mais sa trajectoire déterministe (à la différence de celle d'un avion) peut être calculée très tôt. La défense, face à cette menace de grande vitesse, implique une alerte et une désignation d'objectif précoces par les senseurs de surveillance, une décision d'engagement de la menace très rapide, transmises sans retard aux systèmes d'armes.

Le caractère déterministe de la trajectoire favorise l'alerte et la désignation d'objectif précoces par une fusion multi-senseurs, satellites, radars de veille, avions optiques, très efficace. L'analyse de l'efficacité de la défense passe par l'étude (chronologies, précisions) de cette chaîne d'engagement, c'est-à-dire d'un système de systèmes.

Le missile balistique de longue portée (3000 km) menace un territoire très vaste, à l'échelle de l'Europe mais en revanche il est possible d'engager très tôt des systèmes d'armes de longue portée. L'analyse de l'efficacité de la défense doit alors se faire au niveau du théâtre.

La Défense Aérienne Elargie fait apparaître la nécessité d'une simulation de systèmes de systèmes au niveau du théâtre, d'autant plus que la trajectoire déterministe du missile balistique permet de rendre très fidèle cette simulation. L'Extended Air Defense Test Bed est la solution retenue par l'US Army. La plate-forme SOSIE développée par COSYDE pour la DGA est la solution que nous vous présentons maintenant.

3. Les objectifs de SOSIE
Le principe de SOSIE est de réutiliser des logiciels de simulation existants, dans une plate-forme qui propose pour l'ensemble de ces logiciels une gestion commune des objets et des scénarios d'attaque-défense au travers d'une interface homme-machine conviviale.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

L'utilisation de simulations existantes est d'abord une solution peu coûteuse mais surtout elle a l'avantage d'emporter la confiance de leurs utilisateurs habituels et des clients qui en ont fait la recette.

Une enquête, effectuée par COSYDE pour définir le service attendu de SOSIE par les concepteurs de doctrine, les opérationnels et les ingénieurs en charge de la conception des architectures de défense et des systèmes d'armes, a confirmé cette analyse. Tous ces utilisateurs disaient disposer des simulations nécessaires, mais souhaitaient les voir intégrer dans un centre de simulation de référence.

Les logiciels de simulation existants se répartissent en général selon trois niveaux :

- le niveau duel entre une menace assaillante (avion, missile) et un système d'armes (un contre un),

- le niveau site correspond à la défense d'un site par un ou quelques systèmes d'armes contre un raid aérien ou une salve de missiles balistiques (quelques uns contre quelques uns),

- le niveau théâtre qui traite de l'ensemble du conflit en modélisant les interactions entre toutes les menaces et tous les systèmes de défense (senseurs, systèmes d'armes, BMC^3).

La modélisation, très détaillée dans le duel, se simplifie en général dans les deux autres niveaux pour limiter l'augmentation des temps de calculs liée à celle du nombre d'objets à traiter.

SOSIE met en oeuvre ces trois niveaux de simulation.

L'enquête déjà citée mettait également en évidence l'intérêt des développeurs de doctrine pour la séparation des rôles attaque et défense pour la saisie des scénarios et l'introduction de l'homme dans la boucle. Ces deux fonctionnalités permettent en effet de mieux refléter la réalité des opérations de déploiement de la défense d'une part, de définition des plans d'attaques d'autre part, qui se font le plus souvent sans connaître complètement les plans de l'adversaire.

La séparation des rôles attaque et défense et l'introduction de l'homme dans la boucle sont deux possibilités offertes par SOSIE.

4. La plateforme SOSIE

4.1 Description

A l'issue de sa première étape de développement, la plate-forme SOSIE est un outil d'évaluation d'architectures de défense aérienne élargie, qui simule les systèmes de la menace aérienne et de la menace balistique ainsi que l'ensemble des systèmes de défense potentiels envisagés pour contrer cette menace.

La plate-forme est constituée d'une structure d'accueil logicielle qui permet de manipuler les objets et les scénarios attaque-défense, puis de lancer la simulation choisie parmi les trois proposées.

- SPOOK qui simule la défense de théâtre, met en oeuvre tous les systèmes attaque et défense ; c'est lui qui permet l'évaluation de systèmes de systèmes au niveau théâtre.

- TACSIT permet l'évaluation technique et opérationnelle des systèmes d'armes surface-air de type SAMP/T* et PATRIOT pour la défense de site (100 km x 100 km) contre la menace aérienne et la menace balistique de courte portée (< 1000 km).

- DIAMS permet l'analyse fine du duel d'un intercepteur engagé par son radar de conduite de tir, contre une menace unique, avion, missile de croisière, missile balistique ... DIAMS fournit principalement la probabilité de destruction de la menace (P_k) et permet de calculer les domaines défendus. DIAMS modèlise les systèmes d'armes pour la défense de points, tels que SAMP/T*, PATRIOT, SA12, SA10.

Les simulations SPOOK, TACSIT et DIAMS ont été choisies en particulier pour leur caractère générique, c'est-à-dire leur capacité à modéliser rapidement de nouveaux systèmes. Ce caractère générique est particulièrement précieux pour l'étude et la spécification d'architectures de défense et des systèmes qui les composent.

La structure d'accueil favorise les échanges de données entre simulations ; les tables de P_k, en fonction des configurations de présentation menace-intercepteur, sont calculées à l'aide de DIAMS, elles sont ensuite transmises en entrées des simulations TACSIT et SPOOK ; les cartes de visibilité, compte tenu du terrain, sont élaborées à l'aide de TACSIT et transmises à SPOOK.

Trois consoles sont disponibles qui permettent la séparation des rôles attaque et défense dans la saisie des scénarios. La console blanche distribue les forces, définit la mission. La console rouge crée le scénario d'attaque. La console bleue déploie la défense et son BMC^3. La console blanche permet de limiter pour la console rouge la connaissance du déploiement bleu et réciproquement la connaissance du scénario d'attaque rouge pour la console bleue.

Pendant le déroulement de la simulation, l'ensemble des résultats est disponible sur la console blanche ; sur la console rouge apparaissent les trajectoires des attaquants, le déploiement filtré de la défense et les effets de la défense sur l'attaque ; sur la console bleue apparaissent le déploiement de la défense, les plots radar et les effets de l'attaque sur les objectifs.

Pendant le déroulement de TACSIT, l'attaquant, à partir de la console rouge, peut agir sur les trajectoires des raids d'avion et le défenseur, à partir de la console bleue, peut opérer une désignation d'objectif manuelle.

4.2 L'organisation générale de SOSIE

SOSIE peut être utilisée en mode une console et en mode trois consoles.

L'interface homme-machine doit permettre à l'utilisateur de mettre en oeuvre le plus clairement possible les cinq fonctions principales de SOSIE :

- choix de la configuration,
- gestion des objets,
- gestion des scénarios,
- exécution,
- exploitation.

Le menu général de SOSIE est le premier que rencontre l'utilisateur après s'être connecté. Il présente les cinq fonctions principales.

L'utilisateur ne peut sélectionner une fonction principale qu'à partir du menu général de SOSIE.

Le choix de la configuration permet de définir la configuration logicielle et matérielle. L'utilisateur peut effectuer ce choix directement ou choisir de remplir un questionnaire qui déterminera la (ou les) simulations à utiliser ainsi que le nombre de consoles nécessaires (une ou trois).

La gestion des objets permet de manipuler (définir, modifier, ...) les objets (avion, missile, objectif, radar, satellite, système d'armes, ...) utilisés dans les simulations. Chaque objet est caractérisé par un ensemble de données et stocké dans la base de données objets.

La gestion des scénarios permet d'effectuer toutes les opérations nécessaires à la création et à la modification des scénarios. Elle utilise en entrée la banque de données objets. La création d'un scénario est effectuée en plusieurs étapes successives, choix du terrain, de l'environnement météorologique, allocation des forces, déploiement des objectifs, déploiement des forces bleues, déploiement des forces rouges, enregistrement dans la banque de données scénarios.

Le rôle de la fonction traduction est de convertir les informations provenant des bases de données scénarios et objets dans le format propre à chaque simulation SPOOK, TACSIT et DIAMS.

La fonction exécution permet de lancer, suspendre et d'arrêter une simulation. L'utilisateur peut suspendre TACSIT et SPOOK à chaque instant. La suspension prend effet au premier état stable rencontré dans l'exécution. C'est cette fonction qui permet également de visualiser le déroulement de la simulation sur les consoles.

A la fin de l'exécution, les résultats sont sauvegardés systématiquement en vue de leur exploitation par les utilitaires propres à chaque simulation. L'utilisateur doit indiquer les références qu'il veut donner à ces résultats. L'exploitation des résultats ne peut se faire que sur la console blanche.

4.3 Les modèles de simulation

4.3.1 DIAMS

Généralités

DIAMS est un outil générique de simulation du duel antiaérien qui peut travailler à deux niveaux de finesse de simulation. Les résultats principaux de la simulation sont les probabilités d'interception (Pk), les zones défendues (foot print) peuvent également être calculées.

Un module générique permet une évaluation complète et rapide du duel antiaérien sans entrer dans une analyse fine du comportement des mobiles lors de l'interception finale. La

détermination des zones protégées (foot print) est effectuée à l'aide de ce module.

Un module spécifique est également disponible pour effectuer des études beaucoup plus détaillées du système d'armes.

Les objets et les scénarios
Les scénarios de la simulation mettent généralement en présence un système d'armes antiaérien et un assaillant. L'assaillant est caractérisé par sa trajectoire (altitude, vitesse, manoeuvrabilité), ses signatures radar et infrarouge, ses capacités de brouillage et sa vulnérabilité. Le système de défense est caractérisé par ses moyens de détection, ses algorithmes de trajectographie, son missile intercepteur dont les fonctions (paramètres aérodynamiques, propulsions, guidage/pilotage, guidage final et charge de combat) sont modèlisées en détail.

Lors de l'exécution du scénario, l'assaillant se rapproche suivant une trajectoire pré-programmée. La détection par les radars et la poursuite conduisent à l'initialisation d'une piste. Le missile intercepteur est lancé dès que l'assaillant est considéré en portée. Le missile est guidé vers l'assaillant sur désignation d'objectif externe puis sur autoguidage. La simulation calcule la distance de passage et simule la détonation de la charge de combat. La simulation de l'efficacité de la charge prend en compte le module de vulnérabilité de l'assaillant en face de l'effet de souffle et de la cinématique des fragments.

L'influence du brouillage est prise en compte pendant toute la durée de la simulation.

La simulation est du type temporelle à pas variable qui s'ajuste automatiquement en fonction à la fois de la quantité d'évènements sur la trajectoire du missile et de la finesse de la simulation recherchée. Des analyses statistiques type MONTE CARLO sont possibles.

Description du modèle
DIAMS met en oeuvre six groupes de modules différents :

- le programme principal qui gère la simulation en général, l'intégration des résultats et les entrées / sorties,
- les modules assaillant,
- les modules de détection,
- les modules de poursuite et de politique de tir,
- les modules de simulation de vol de l'intercepteur sol-air,
- les modules létalité de la charge de combat et de vulnérabilité de l'assaillant.

A l'intérieur de chaque groupe les fonctions sont modélisées de manière spécifique. Pour chaque fonction importante il existe deux algorithmes dont un générique pour répondre aux besoins de modélisation rapide surtout lorsqu'il s'agit d'introduire de nouveaux systèmes.

Les entrées / sorties
Les paramètres d'entrée se répartissent selon trois catégories :

- paramètres concernant le système d'arme sol-air,
- paramètres concernant l'assaillant,
- paramètres spécifiques du scénario et de l'environnement de la simulation.

Les sorties peuvent être à la fois présentées sous forme texte ou graphique. Les paramètres sorties concernent les trajectoires du missile intercepteur et de l'assaillant, le résumé des évènements intervenus au cours de la simulation.

4.3.2 TACSIT

Généralités
TACSIT est une simulation technico-opérationnelle qui permet d'analyser l'efficacité au niveau du site d'une défense anti-aérienne face à différents scénarios d'attaque en prenant en compte l'environnement physique de la zone considérée et la mission opérationnelle de protection à réaliser. Cette analyse peut être absolue (mise en évidence de points faibles et études d'amélioration) ou relative (comparaison entre versions ou études paramétriques).

Les modélisations des systèmes introduits dans TACSIT s'appuient sur des données de haut niveau d'abstraction, générées et validées par ailleurs à l'aide de modèles techniques plus détaillés. Par définition, le modèle de comportement est dynamique et couvre en général, pour l'ensemble des intervenants, les phases de préparation puis de déroulement d'un combat attaque/défense évoluant dans un cadre réaliste d'environnement physique.

Objets simulés

- Missiles moyenne portée
  La trajectoire du missile est calculée en prenant en compte sa vitesse estimée à partir du bilan trainée/poussée et de l'incidence. La loi de guidage utilisée est la navigation proportionnelle.

- Radars
  La modélisation des radars est réalisée à partir d'une estimation du rapport signal/bruit prenant en compte les paramètres de l'équation radar (puissance crête, durée d'impulsion, gains d'antenne, longueur d'onde, surface équivalente radar de la cible, distance radar-cible, pertes atmosphériques, ...).

  L'espace est découpé en un certain nombre de secteurs séparés en site. Des caractéristiques différentes (constante radar, thème de veille) peuvent être définies pour chaque secteur.

- Guerre électronique
  Modélisation de brouilleurs (SSJ et SOJ) et de lance-leurres.

- Commande et contrôle (C^2)
  La simulation prend en compte les liaisons entre éléments de la défense et les fonctions de commande et contrôle (identification, corrélation, évaluation de la menace, atteignabilité, classement d'urgence, interceptabilité, engageabilité, élaboration du plan d'engagement, commande et contrôle des tirs ...).

- Avions d'attaque et missiles de croisière
  Les trajectoires sont caractérisées par des points de passage avec possibilité de suivi de terrain.

- Missiles balistiques
  La trajectoire finale est modélisée par point.

  La SER est définie en fonction de la fréquence.

  Les systèmes d'armes courte portée, la veille infra-rouge et l'artillerie sont également modélisés pour les besoins de la défense anti-aérienne courte portée classique.

Génération de scénarios
En phase de préparation, l'activité majeure est de définir et d'implanter les dispositifs de défense et d'attaque. Ces manipulations d'ensembles aboutissent respectivement au déploiement des systèmes d'armes et à l'établissement des plans d'attaque (e.g. plans de vol pour des vecteurs aériens), en tenant compte du terrain, de la météo, de l'intervisibilité (radar, optique). Elles sont en général assurées par le dialogue interactif entre l'utilisateur et la machine.

Description du modèle
Il effectue les simulations des séquences d'engagement : surveillance (calcul du S/B, détermination de la Pd et tirage aléatoire, formation du plot), pistage (création des pistes locales, associations plots/pistes, estimation de la cinématique), corrélations (restitution d'une situation tactique aérienne), identification, évaluation de la menace, assignation armes (choix de la batterie, choix de la rampe), engagement et interception (évaluation de la miss-distance, détermination du SSKP, tirage aléatoire).

4.3.3 SPOOK

Généralités
SPOOK est un simulateur de type théâtre, événementiel et orienté objet, totalement interactif.

Cet outil de simulation, écrit en langage COMONLISP,C et FORTRAN, a pour mission d'aider les acteurs de la défense aérienne à dimensionner, confronter et évaluer l'attaque et la défense dans des conflits de défense aérienne élargie.

Tous les constituants de la défense peuvent être pris en compte : satellite géostationnaire, radar, systèmes d'interception, SIC (Systèmes d'Information et de Communication) ainsi que toute la menace aérienne : avions, missiles balistiques et de croisière, brouilleurs...

Objets simulés
Il existe quatre classes principales d'objets de défense : les senseurs, les intercepteurs, les avions et les sites à protéger.

- Senseur
  Deux types de senseurs sont représentés :

- senseur électromagnétique caractérisé essentiellement par un domaine maximum de détection (site, gisement, distance), une

constante radar, la fréquence de veille et de poursuite et la sensibilité face au brouillage,
- senseur infrarouge.

- Système d'interception :

Cet objet est caractérisé par un domaine d'action géométrique, une vitesse moyenne de l'intercepteur et différents délais : réaction du système, mise à feu, délais entre deux tirs... A chaque système d'interception est associée une table de Pk, fonction du type de la cible, et éventuellement de la position de l'interception par rapport au lanceur.

- Site à protéger

En dehors des éléments de la défense qui peuvent eux-mêmes constituer des sites à protéger (par exemple un radar de Défense aérienne) deux types de sites sont simulés : les bases aériennes et les sites industriels. Une base aérienne est caractérisée par le nombre de pistes. La vulnérabilité des sites est calculée pour certains points sensibles (les pistes pour une base aérienne ou l'aérien d'un radar par exemple) par rapport à la mission du site.

La destruction de tous les points sensibles entraîne la destruction du site.

- Avions intercepteurs

Ils sont caractérisés par un rayon d'action et les systèmes d'armes air-air embarqués (senseur électromagnétique et missile). Leurs trajectoires sont construites point à point, chaque point étant caractérisé par la date, la position géographique (longitude, latitude) l'altitude et le vecteur vitesse.

Tous ces objets sont reliés par l'intermédiaire du SIC. Un réseau SIC est caractérisé par un certain nombre de centres de commandements affectés aux sites ou systèmes d'armes et reliés entre eux par des réseaux de communications. Les liaisons entre deux centres sont caractérisées par un flux d'informations et un délai de transmissions tenant compte de la vitesse de transmission des informations.

Il existe quatre objets de l'attaque :

- Missile balistique

Il est caractérisé par :

- une portée maximum ; les points de passage de la trajectoire sont ensuite calculés automatiquement en fonction du type de la trajectoire : énergie minimum, tendue, plongeante,
- deux valeurs de SIR pour la phase propulsée et pour la phase balistique,
- deux valeurs de SER suivant l'angle de présentation.

- Missiles de croisière

La trajectoire de missile de croisière est construite point par point comme celle d'un avion en fonction des besoins du scénario. La SER est également indiquée (en fonction de la fréquence).

- Avions

Quelle que soit leur nature : chasseurs, bombardiers ou chasseurs-bombardiers leur armement est indiqué (systèmes d'armes missiles air-sol ou air-air, bombes, moyens de guerre électronique ...). Un test de cohérence est effectué lors de la définition d'une plateforme pour les besoins d'un scénario. La trajectoire est introduite point par point. La SER est également définie.

- Brouilleurs

Ils sont définis par une plateforme aérienne dont la trajectoire est introduite point par point et par la densité de puissance électromagnétique rayonnée.

Générations de scénarios

Les sites à protéger sont déployés sur le théâtre par l'intermédiaire de leurs coordonnées géographiques. Les bases aériennes peuvent comporter des quantités variables d'intercepteurs aériens prêts au décollage. Pour les besoins de la simulation le préavis d'alerte peut être modulé.

Les éléments de la défense sont également repérés par leurs coordonnées géographiques. La portée des senseurs et des intercepteurs est calculée en fonction du terrain et représentée sur les cartes du théâtre.

Ces éléments sont reliés par un Système d'Information et de Communication dans lequel les niveaux hiérarchiques sont définis. Les délais et flux d'informations peuvent être modifiés.

C'est dans le SIC que sont définis les politiques de tirs des missiles sol-air, les affectations des systèmes de défense en fonction de la menace, les délais d'alerte, les décisions d'engagement des intercepteurs aériens en quantité et par base aérienne selon les détections effectuées par les senseurs.

Les éléments de l'attaque sont déployés soit par leur point de lancement et d'impact en ce qui concerne les missiles balistiques ou leur trajectoire pour les missiles de croisière. Les attaques aériennes sont définies par la nature et la quantité des avions assaillants et leur armement. Dans une attaque groupée seule la trajectoire du leader est introduite, les autres appareils sont positionnés par rapport au leader.

Utilisation

L'utilisateur a la possibilité par l'interface graphique, de supprimer, ajouter ou déplacer des systèmes et modifier éventuellement leurs caractéristiques : réduire ou augmenter la couverture en gisement, modifier son orientation...
De même, la création des trajectoires des menaces balistiques est simple et permet donc de modifier très rapidement le scénario d'attaque.

Le déroulement d'une simulation peut s'effectuer suivant deux modes :

- mode pas à pas : il permet de comprendre le déroulement du scénario et de contrôler les passages de main entre les différents constituants,
- mode statistique : application de la méthode Monté Carlo.

5. Flexibilite de la configuration SOSIE

La plate-forme SOSIE, qui est aujourd'hui opérationnelle, est donc constituée d'une structure d'accueil et de trois simulations SPOOK, TACSIT, DIAMS.

Elle est adaptée aux besoins des études actuellement menées en DAE :

- étude détaillée de l'efficacité de systèmes d'armes surface-air de moyenne portée contre la menace aérienne et les missiles balistiques de courte et moyenne portée (DIAMS, TACSIT),
- conception d'architectures de défense contre l'ensemble de la menace, y compris les missiles balistiques de longue portée (SPOOK).

De par sa conception, la configuration de la plate-forme SOSIE peut évoluer facilement en fonction des besoins.

D'autres simulations peuvent venir compléter ou remplacer celles existantes aujourd'hui.

La structure d'accueil continuera à fournir l'environnement commun d'exploitation décrit précédemment.

L'introduction d'un nouveau logiciel de simulation ne nécessitera que le développement d'un traducteur.

6. Conclusion

L'un des intérêts de SOSIE réside dans l'utilisation des modèles de simulations existants et la possibilité de les faire dialoguer. La flexibilité de SOSIE résultant de sa conception en structure ouverte comme indiqué précédemment permet d'intégrer d'autres modèles de simulations.

Il est déjà prévu d'intégrer des modèles de simulations au niveau duel pour la modélisation du canal de tir antiballistique SAMPT* ainsi que des modèles de simulations du combat air-air ou un modèle détaillé de système d'information et de communication représentatifs des réseaux en développement. A moyen terme l'objectif est d'étendre le catalogue des modèles de simulations compatibles aux trois niveaux de simulation. En parallèle il sera procédé à l'enrichissement de la base de données et des scénarios. La fonction gestion de configuration sera développée en conséquence afin d'apporter une aide à l'utilisateur quant à la définition de la meilleure "architecture" de simulation pour résoudre son problème.

Deux types d'évolutions, à partir de la plateforme SOSIE actuelle, peuvent être envisagées. Celle qui correspond à l'établissement d'un noeud de simulation pour les concepteurs mais également les stratèges des Etat Major. Ce noeud de simulation devra être interopérable avec les autres noeuds étrangers équivalents en particulier l'EADTB.

Une autre évolution possible pourrait être un simulateur portable pour l'entrainement des forces. La configuration sera alors fixe, les objets définis et seuls les scénarios pourront être modifiés pour satisfaire aux besoins d'entrainement.

AGARD Symposium 17-20 May 1994

TMD Detection and Tracking Using Improved AWACS Sensors

Steve Petersen, Lt Col, USAF
Div. Chief, Advanced Capabilities Division
Ballistic Missile Defense Organization
System Applications Directorate (BMDO/AQS)
The Pentagon (1E1020)
Washington, D. C. 20301-7100

Yasuhiro Kinashi
Nichols Research Corporation
1604 Spring Hill Road, Suite #200
Vienna, VA 22182-7510

Daniel Leslie, Ph.D.
W. J. Schafer Associates, Inc.
1901 N. Fort Myer Drive, Suite #800
Arlington, VA 22209

(Abstract)

In response to a congressional goal for the United States to provide highly effective theater missile defenses (TMD), Ballistic Missile Defense Organization (BMDO) has enacted its acquisition plan to develop, test, and field User Operational Evaluation Systems (UOES) prototypes for the THAAD/GBR and Standard Missile II weapon systems before the year 2000. The UOES configurations are designed for the purpose of supporting integrated active defense testing and provide limited operational capability in the event of a national emergency. The principal motivation for the UOES acquisition structure is to provide an essential TMD active defense system in countering emerging proliferation of increasingly long-range theater ballistic missiles (TBMs) capability by countries in politically unstable regions.

Previous design studies have highlighted the benefits of early warning and cueing from external surveillance sensors, increasing the reaction time and engagement options of the active defense elements to counteract the attacking TBMs. These options for expanding the engagement battle space may be essential, if not crucial, for successful very low leakage defense.

This paper identifies an UOES version of an airborne surveillance sensor funded by the BMDO. The sensors will be integrated into an operational AWACS E-3 upgrade program. This BMDO program initiative is called Extended Airborne Global Launch Evaluator, or EAGLE. Initial Operational Capability (IOC) of the EAGLE system will be ready in time to support the THAAD/GBR UOES capability. This airborne system, when developed, will consist of a passive infrared surveillance sensor (IRSS) with an active laser-ranger, on board an upgraded AWACS E3 aircraft to operate effectively in the TMD mission. The objective for the EAGLE is to field, in a reasonably short time and at a relatively low cost, a cueing sensor capability in regional conflicts to augment the existing space-based surveillance systems.

With autonomous surveillance capability to search a wide-sector field, the EAGLE can detect and track boosting TBMs shortly after launch or as they break the clouds. Its passive IR sensor can also detect and track warm hardbody targets. Together with its laser-ranger, it is able to determine, immediately after the booster burn-out, very precise target state vectors that are accurate enough to predict their eventual impact points, to cue fire control radars, and to engage the weapons, if needed.

Its primary TMD mission is to provide precise cueing of fire control radars to initiate the active defense weapon systems. Accurate cues from the EAGLE will off load radar resources to enable earlier detection of the targets at longer extended ranges, thereby increasing the interceptor battlespace for potentially more effective defense engagements and opportunities. It can also provide a precise early warning message to enable immediate TBM attack assessment and appropriate selection of defense engagement options by the battle manager. The functions of the sensor suite can be distributed, such that it can be tasked independently to observe the threat intercept, while providing continuous surveillance of new TBM launches, to support the kill assessment function for shoot-look-shoot opportunities. Another potential function that can be performed by the EAGLE is the estimation of TBM launch points (LPE) for counterforce support.

This technical paper provides an expanded discussion of the EAGLE's mission roles, specific system functions, and its detection and tracking performance capability. The paper also addresses the sensor and the laser subsystem design characteristics and operational modes required to accomplish all its functions. Initial analyses indicate that the impact of scattering and absorption of the IR signatures and laser signals will be minimal on the performance of the system. Recent satellite data provides measurement of atmospheric extinction. Propagation statistics, based on satellite observations are presented for global regions of interest to TMD.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

1.0 INTRODUCTION

The Ballistic Missile Defense Organization (BMDO) with support from the Air Force is planning to develop an User Operational Evaluation System (UOES) version of the airborne sensor payload for TMD surveillance. The system will consist of an infrared surveillance sensor (IRSS) with a laser-ranger on board an AWACS E-3 aircraft to support Theater Missile Defense (TMD) mission against tactical ballistic missiles (TBMs). This system is called Extended Airborne Global Launch Evaluator, or EAGLE. The EAGLE's mission is to support TMD active defense systems with early and accurate track data for the purpose of single-beam cueing of the fire control (F/C) radars. supporting integrated active defense testing and provide limited operational capability for a national emergency. Prototype delivery coincides with the Theater High Altitude Area Defense/Ground Based Radar (THAAD/GBR) and standard missile 2-block 4A UOES development schedules.

1.1 Background

In response to congressional direction to provide highly effective TMD capability, BMDO is developing, testing, and fielding UOES prototypes for the Army's THAAD/GBR and the Navy's SM-II Block 4A weapon systems in the late 1990's. Previous design studies have highlighted the benefits of early warning and cueing from external surveillance sensors, increasing the reaction time and engagement options of the active defense elements to counteract the attacking TBMs. These options for expanding the engagement battle space may be essential, if not crucial, for successful leak-proof defense. The objective for the EAGLE Program is to field, in a reasonably short time and at a relatively low cost, a cueing sensor capability in regional conflicts to augment or substitute for existing space-based surveillance systems.

2.0 AIRBORNE SURVEILLANCE MISSION DEFINITION

The primary mission for TMD is a protection of large regional areas and high valued point targets against TBMs. In support of this mission, the upgraded AWACS, or EAGLE, will be required to perform the necessary surveillance functions for detecting TBM launches and providing accurate tracks on them.

The EAGLE, as a cueing sensor, provides the following surveillance functions:

- Early warning, necessary to alert and activate active defense elements;
- Attack assessment support, to characterize the raid and predict their intended impact point locations;
- Cueing to the F/C radars, for earlier acquisition/tracking and weapon commit and engagement; and
- Kill assessment for intercept scoring.

With autonomous surveillance capability to search a wide-sector field, the EAGLE can detect and track boosting TBMs shortly after their launch or as they break the clouds. With its laser-ranger, EAGLE computes precise target state vectors accurate enough to cue F/C radars for single-beam acquisition. It can also function as an ancillary surveillance asset for counterforce support by computing a TBM launch point estimate (LPE).

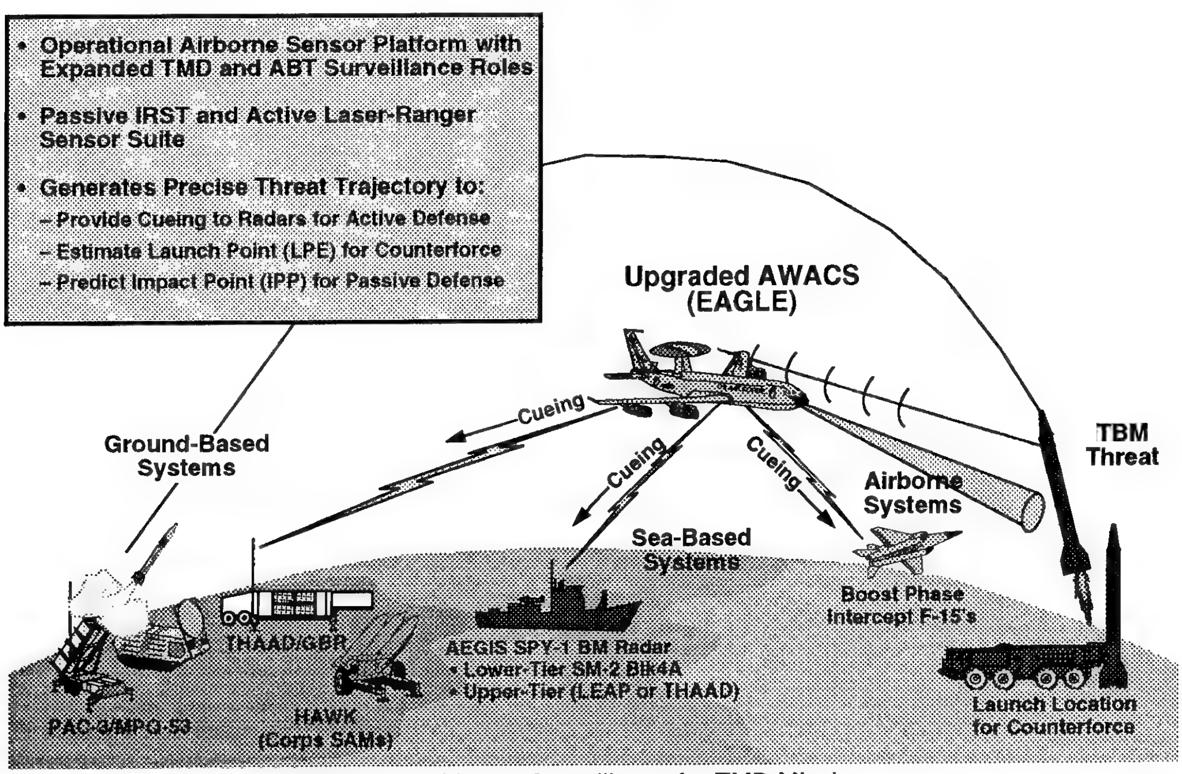


Figure 1. Airborne Surveillance for TMD Mission

2.1 Cueing Requirements

Accurate cues from the EAGLE enable earlier detection of the targets at longer extended ranges, thereby increasing the interceptor battle space for potentially more effective defense engagements and opportunities. It can also provide precise early warning messages to enable immediate TBM attack assessment and appropriate selection of defense engagement options by the battle manager. Its ability to compute a very accurate target state vector and IPP, shortly after the booster burn-out, can help to support the active defense's weapon engagement selection and weapon-to-target assignment (WTA) functions. The functions of the sensor suite can be distributed, such that it can be tasked independently to observe the threat intercept, while providing continuous surveillance of new TBM launches, to support the kill assessment function for multiple shoot-look-shoot opportunities.

All military services are rigorously pursuing acquisition programs to develop their TMD active defense systems. The US Army has a Multi-mode Patriot Upgrade No. 3 (PAC-3) or Extended Range Interceptor (ERINT) with the MPQ-53 F/C radar for a limited area defense and the THAAD/GBR for a wide-area defense; the Navy's Aegis AN/SPY-1 radar supports a lower-tier SM-II variant missile and the USMC's upgraded HAWK with TPS-59 surveillance radars.

2.2 Surveillance Field Coverage Requirements

A detection range envelope of approximately 500 km provides adequate coverage of nearly all representative theater campaigns. Longer ranges may be preferred for early warning of in-range launches and tracking of longer trajectory threats. To substantiate this claim, the two most representative campaigns are presented below.

The Middle-East Campaign shown in Figure 2 was created solely for modeling purposes. It contains a first wave attack that lasts about 1200 seconds consisting of mostly short range (<300 km) and medium range (300–600 km) missiles with few intermediate range (600–1500 km) TBMs from inland IRAQ.

For a defense surveillance system, a single AWACS platform patrolling outside of Iraqi airspace can provide full coverage of TBM attacks to Israel. For additional surveillance, another AWACS platform, near a Kuwait border, is required to provide the coverage of all potential TBM attacks to the other ally territories.

Our analysis shows that an alternate platform operating at a higher altitude does not provide significantly improved coverage for clear blue sky conditions. The detection sensitivity is addressed later in the paper.

Another example is a North Korean Campaign model. Short and medium range missile attacks are directed at South Korea and intermediate range TBMs toward Japan. Given the surveillance envelope defined above for the TBMD-capable AWACS, only single platform patrolling as shown in Figure 3, could provide full coverage of all TBM attacks. All targets, including short range missiles, can be easily acquired from early boost—assuming favorable weather conditions and reasonable earth-terrain contours.

Both engagement scenarios show that wide azimuth field coverage (~180 degrees) is required for viewing of boosting missiles. For total coverage of the entire missile trajectory, a nearly 360 degree field of regard is necessary.

For a vertical field coverage, a boost phase missile detection and tracking can be achieved by viewing a

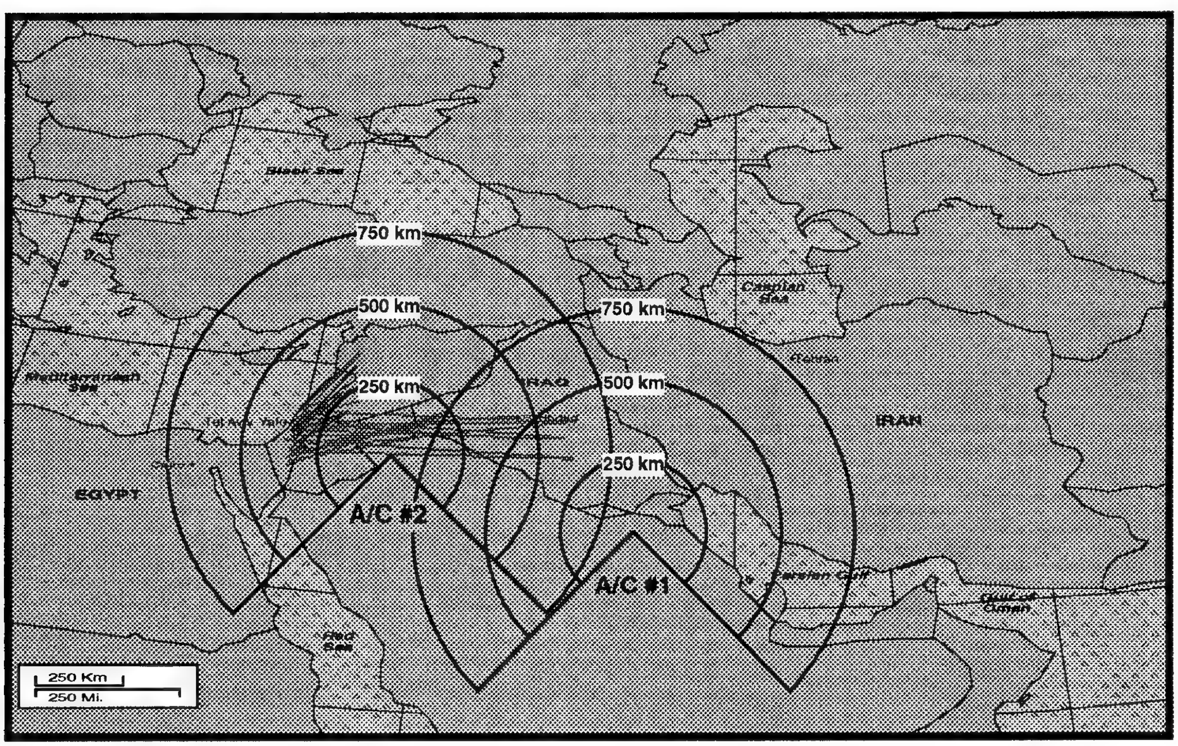


Figure 2. AWACS Field Coverage Requirements for Middle Eastern Campaign

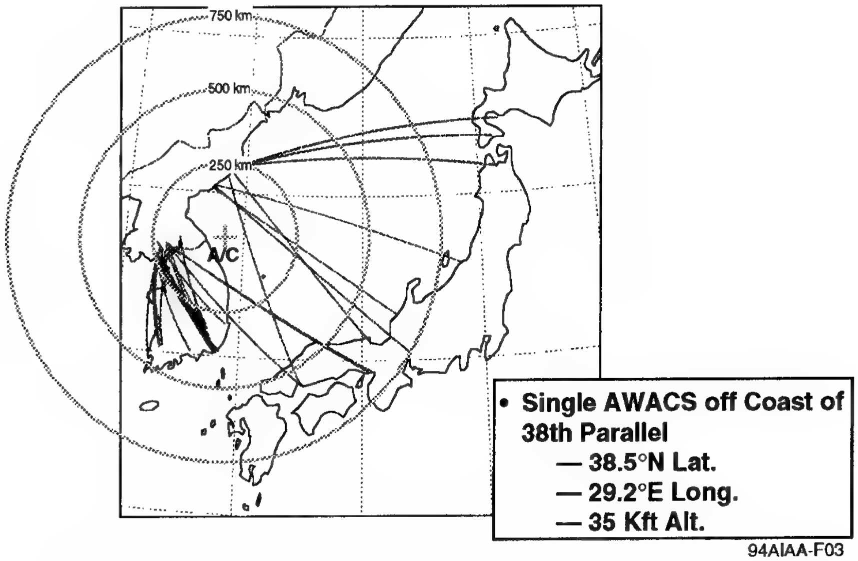


Figure 3. AWACS Field Coverage Requirements for North Korean Campaign

small elevation field-of-view (~10 degrees or less) along the local horizon. Target tracking during the post-boost phases requires high and wide elevation field coverage, especially as the TBMs are closing in toward the platform. The implications on sensor design and operation are that for boost phase detection and tracking, a fast scanning sensor with continuous viewing near local horizon would be desired.

Multi-mode coverage operation with separate surveillance and tracking sensors may provide more flexibility and better total coverage. One implementation is to perform the search and early acquisition functions, then separately maintain high-precision ballistic tracking and target states convergence with a second sensor. One sensor concept of operations is illustrated in Figure 4.

2.3. AWACS Platform Constraints
AWACS was baselined as the platform for the EAGLE system based on the Air Force's strong operational interest and the existence of C3 resources aboard the aircraft. TBM surveillance fits well with existing AWACS surveillance and control missions.

2.3.1 Physical Integration Constraints
The location of the EAGLE sensor suite is currently open. An initial recommendation, based on last year's design feasibility study sponsored by the AWACS program office, was at the opposite edge of the radar rotordome. Further studies identified the advantages of a fuselage-mounted design. The integration issues associated with the selected sensor mounting design and location with respect to the aircraft structure will be resolved during sensor design/integration in the design development phase. The field-of-view constraints for the each sensor mounting location and the impacts on aircraft aerodynamics, must be carefully considered. The overall IRSS/Ladar system for the EAGLE must provide isolation from the aircraft dynamics and avoid electro-magnetic interference (EMI) with existing subsystems. The total sensor system must not exceed allocated size, weight, and power dissipation limits.

2.3.2 Operational Limits
AWACS operates at a stand-off range from the enemy border. This study assumed an AWACS operating altitude of 35 kft for TBMD. A typical loiter period is 8 hours per aircraft, with less time for extended operations at a higher altitude. Twenty-four hour continuous coverage by aircraft requires a fleet of five.

The required field coverage is a total 360 degree azimuth field of regard (limited by airframe occultation) with an elevation field of regard from 15 degrees below the local horizon to a limit of 80 degrees above the horizon. These operational and engagement constraints must be reflected in the system design.

2.4 EAGLE Sensor system Design Constraints
In order to conform to the weight and aerodynamic constraints (~200 kg), the study assumed a telescope aperture of 20–25 cm diameter and common shared optics for the passive IR sensor and a laser receiver. Although smaller aperture for a passive-only sensor may be suitable, the telescope aperture size is predominantly driven by the transmitter power limitation and the required detection range for the laser-ranger.

2.4.1 Passive IR Sensor
The passive IRSS will operate, as a minimum, in a MWIR band to perform a warm hardbody detection during the TBM ascent phase.

2.4.2 Laser Ranger
The laser radar must satisfy several design constraints. First, it must be eye safe at the transmitter aperture. As long as the laser wavelength is beyond about 1.4μ, and the short-pulse energy is several joules at most, the fluence at the exit aperture, even if underfilled, will be well below MPE (maximum permissible exposure) levels. The laser system will be designed to operate with an aperture no larger than 20–25 cm diameter, and will be integrated with the passive system. The mass, volume, and electrical requirements shall require no substantial modification of the aircraft structure. A 20–

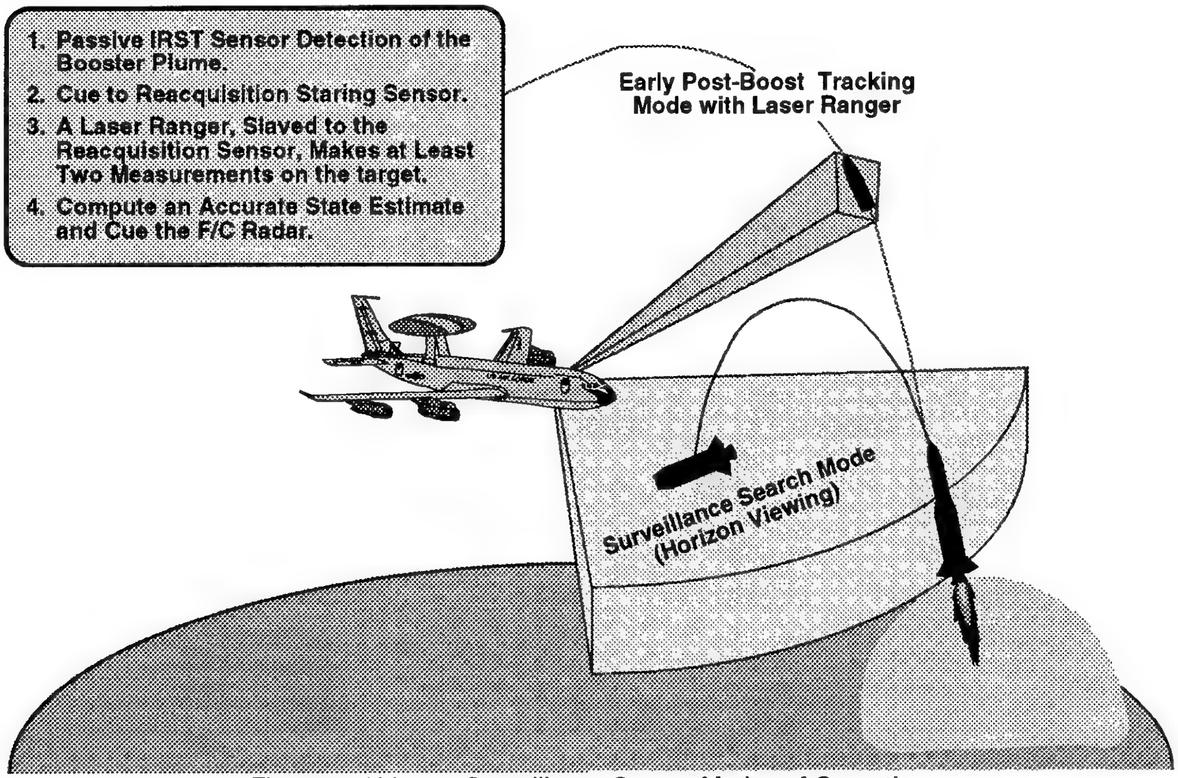


Figure 4. Airborne Surveillance Sensor Modes of Operation

50 Hz system is expected to perform the specified TMD track mission.

2.4.3 Pointing and Control

The pointing and control subsystem will be designed to maintain the accuracy (jitter, bias, and drift) required for the sensor boresight pointing and control for search techniques needed to acquire the targets. This includes, aside from an integrated gimbal system and inertial measurement unit (IMU), other subsystem components to dampen vibration and other motion errors induced from the aircraft structures, and interfaces to the navigation subsystem. The design must balance the pointing requirement for both passive IR sensor and laser-ranger.

Previous design analyses by others have indicated that 10–20 μrad pointing stability and 100 μrad absolute bias errors for a real-time processing can be very reasonably attained from the current off-the-shelf components.

2.4.4 On-Board Processing

The EAGLE will be equipped with a dedicated, stand-alone, on-board processor to convert raw sensor measurement data to useful target information that can be transmitted via the JTIDS (Link 16) network. In order to compute the target states, the computer will have access to the aircraft attitude and navigation data, and sensor boresight attitude and alignment information.

3.0 AWACS/EAGLE PERFORMANCE

The BMDO/TMD Sensor Directorate initiated a technology feasibility study task in the spring of 1993 to perform feasibility and performance analysis of the AWACS/EAGLE concept. The study quantified EAGLE's detection sensitivity, tracking capability and impact of early cueing on the active defense battle space. The analysis was limited to the two weapon systems similar to the PAC-3 point defense and THAAD area defense systems. The results of the analysis are discussed below.

Initial analyses indicate that the impact of scattering and absorption of the infrared signatures and laser signals will be minimal on the performance of the system. Recent NASA SAGE satellite data provides measurement of atmospheric extinction. Propagation statistics based on satellite observations are presented for global regions of interest to TMD.

3.1 IRSS Detection/Acquisition Capability

The Passive IR surveillance sensor (IRSS) to performs wide-area autonomous search and acquires a boosting TBM shortly after its launch or as it breaks through the cloud cover. The detection and tracking of TBMs during their initial boost phase is usually accomplished by a fast scanning sensor, operating in either short (2–3 μm) and medium (3–5 μm) wavebands. Because of extremely bright and hot IR plume signatures from Scud-type TBMs, the signatures are easily detectable with high signal-to-clutter ratios (>20:1) and the target viewing is only limited by the hard earth limit (see Figure 5).

For short to medium range TBMs (i.e., 300–600 km), the boost burn out occurs at a modest altitude (20–50 km); hence, a detection range for a scanning MWIR sensor drops to 600 km or less. This is directly dependent on the apparent target skin temperature assumed, based on the ascent heating. With a minimal ascent heating for short range TBMs, a detection range by a fast-scanning MWIR sensor could drop to 200 km.

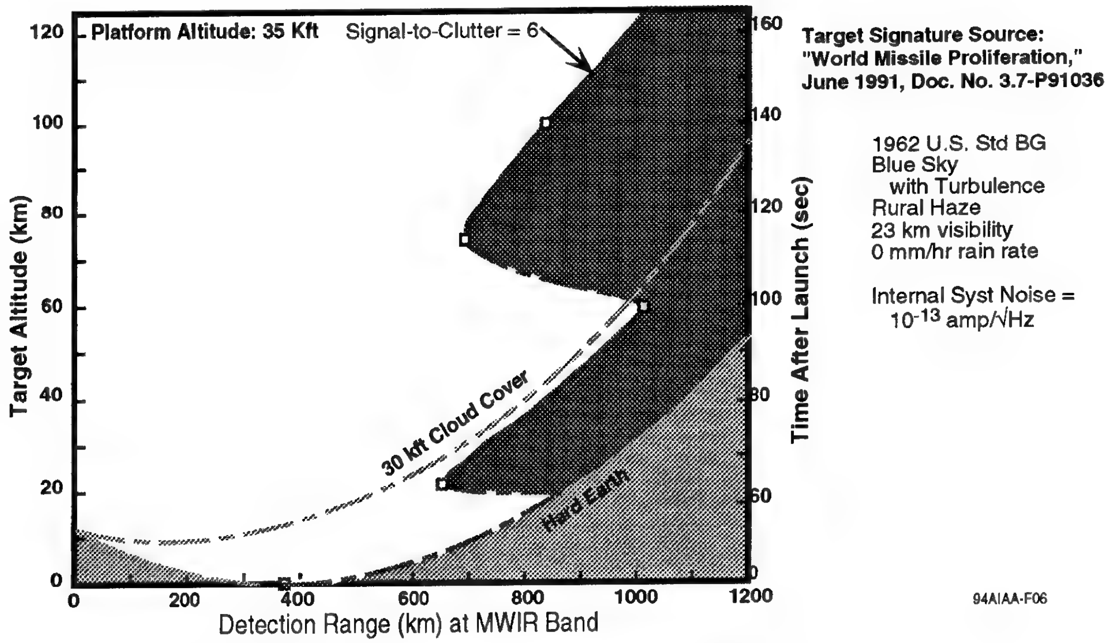


Figure 5. Passive IR Detection Sensitivity for a 600-km TBM Target

If the sensor suite includes a scanning SWIR (or MWIR) for the booster plume detection and tracking and a separate staring reacquisition sensor for the hardbody target tracking, as suggested in the previous section, there are enough signal-to-noise in the MWIR band to detect an ambient-temperature (~350°K) target at a ranges beyond 500 km. The difference in the increased performance is the longer detector dwell time on the target.

One obvious performance issue for the airborne sensor operating in IR bands is that viewing geometry limits combined with cloud cover or other non-ideal weather conditions may severely limit its detection range. A 30 kft altitude was assumed as a nominal cloud top for this analysis.

Figure 5 shows detection range limits due to a complete cloud cover at 30 kft. The figure shows that TBMs are not detectable until at least 10 km altitude. Although this limits boost phase detection of short range TBMs, medium and longer range missiles can be seen at long ranges (>600 km) before their burn-out.

This type of the analysis is dependent on the data sources of signatures and modeling fidelity. Since, there is a lack of reliable measured data on the TBM target signatures, this analysis took a reasonably conservative approach to quantify predicted performance.

3.2 Laser Radar Capability

Beyond 1.4μ there are at least three types of laser radar systems which could provide the required precision ranging capability. The first type includes several techniques for shifting Nd:YAG laser radiation from 1.06μ to longer wavelengths. Raman shifting in gases such as CH_4 is a relatively mature technique to provide eye-safe wavelengths, but may not be capable of operating at high fluence or high repetition rate. Frequency shifting 1.06μ radiation in an optical parametric oscillator (OPO) such as KTP crystal can provide 1.571μ radiation to the 0.5 J level with current crystal sizes, and excellent InGaAs avalanche photodiodes work well in this region. A number of wavelengths between 1.5 and 1.6μ are available depending on choice of OPO crystal and pump wavelength. A second type of laser is directly pumped solid state devices such as Ho:YAG or Tu:YAG which operate in the 2.0–2.1μ region. Several Joule pulses are available from these devices, but relatively noisy detectors may require heterodyne operation. The third type of laser radar system is the CO_2 gas laser, optimized for laser radar use. Several hundred distinct laser lines are available between 9 and 12μ. For long atmospheric propagation paths an isotope of C or O is used to minimize absorption by atmospheric CO_2. The CO_2 laser technology is relatively mature, but high repetition rate devices must use mechanical blowers to circulate the gas. Heterodyne detection would probably be used, and Doppler as well as range data may be available for tracking.

The laser pointing control is integrated with the IRSS. An intermediate IR focal plane could be used to provide 10 μrad target location precision to a calibrated fast steering mirror. The system will be capable of addressing multiple targets to acquire precise range and angle data.

3.3 Atmospheric Effects

The principal atmospheric effects on laser propagation from EAGLE include aerosol scattering and absorption, and molecular scattering and absorption. The following plot summarizes the total extinction provided by a (cloud-free) atmosphere at several laser wavelengths, as modeled using the AFGL FASCOD3P propagation code and HITRAN92 database. Transmission is calculated from the extinction curves by integrating along the propagation path. Excellent transmission exists

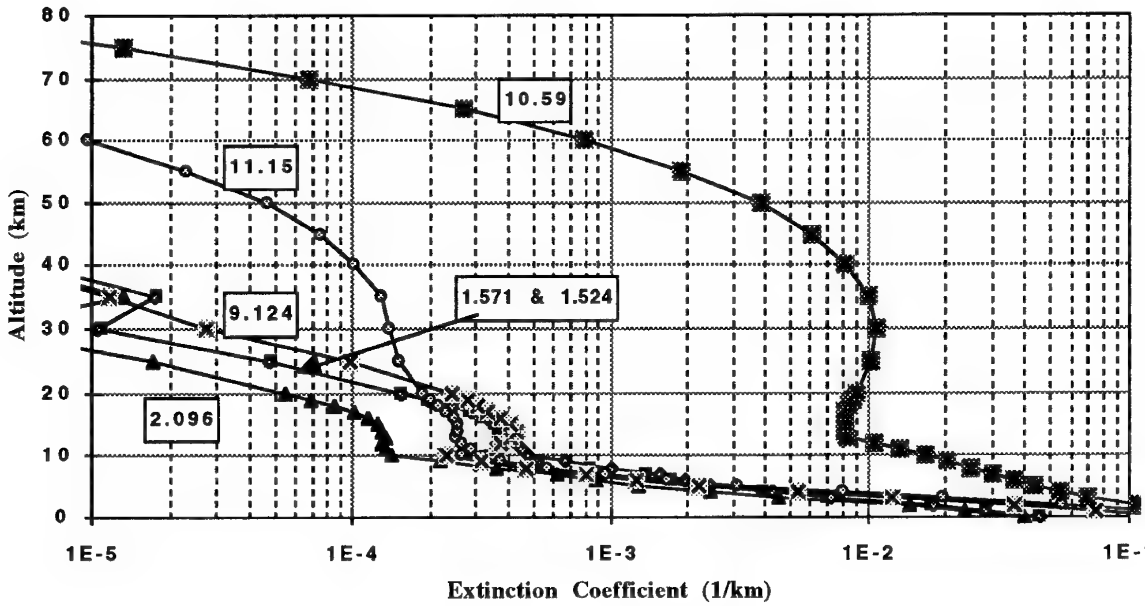


Figure 6. Atmospheric extinction coefficient vs. altitude at six laser wavelengths. A mid-latitude summer atmosphere was assumed, with a rural-23 km boundary layer, and background stratospheric/moderate volcanic stratospheric model.

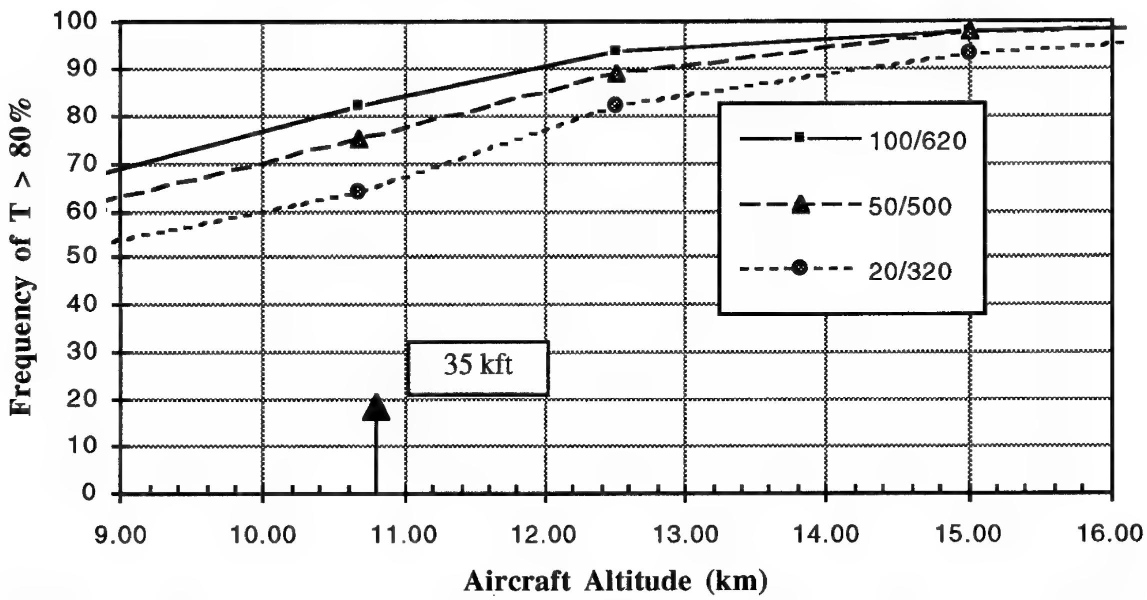


Figure 7. Frequency of occurrence of acceptable transmission (T>80%) vs. aircraft altitude for three TMD propagation paths, using SAGE satellite data for the Mid-East, 1985–1989.

for TMD optical paths for five of the six wavelengths. Self absorption at 10.59μ by ambient CO_2 would prevent use of the normal isotope.

Assessment of the impact of clouds and volcanic aerosols on airborne laser operation has been recently performed for the USAF Phillips Laboratory Airborne Laser (ABL) program.[1] In that study over eight years of limb-view data from the NASA SAGE satellite were used to assess the impact of clouds and volcanic aerosols on ABL propagation. The SAGE data provides direct optical measurement of extinction, with near-global coverage, and over 70,000 profiles were used in the analysis. Laser transmission was calculated using measured extinction profiles for the Mid-East, for TMD geometries. These included propagation from an aircraft to short, medium, and long range targets at altitude/slant ranges of 20/320, 50/500, and 100/620 km. The frequency of acceptable transmission, arbitrarily defined as >80%, was calculated. This method of accounting for clouds is biased low since cloud occurrences over the entire earth limb were used.

From Figure 7 we see that for an aircraft at 35,000 feet, medium and long range targets are available over 70–

80% of the time. Also, post-burnout altitudes are even higher, improving transmission.

3.4 Tracking Performance

The passive IRSS, together with an active laser-ranger, must establish an early track on the boosting TBMs, quickly converge on accurate target states to cue the F/C radar. For the boost-phase tracking, a post-flight data analysis on a recent BMDO-sponsored TMD flight experiment demonstrated booster tracking performance based on data fusion of active ranging by ground radars and a passive airborne sensor on an experimental HALO (High Altitude Observatory) aircraft.[2] Performance results of 100–500m root-sum-square (RSS) accuracies were obtained from less accurate instruments with relatively poor engagement geometries. The analysis also showed that a passive sensor with angles-only measurements can maintain an accurate track on a boosting missile with a single measurement by an active ranging to initiate the track. For an operational system, more frequent ranging would be assumed, but this does show an extent of the system performance feasibility. The EAGLE system with co-aligned sensors and more accurate instruments should easily surpass the best experimental result obtained, at even longer detection ranges.

One of the most critical points in the trajectory may be immediately after the booster burn-out. This is the time from which the accurate convergence of the ballistic track is established. Typical performance of a monocular track processing by a passive sensor may take about 100 to 150 seconds to converge on an accurate track estimate—this is dependent on engagement dynamics; the stereo processing of the passive sensors takes between 50 and 100 seconds (or 5–6 hits at a regular 5 to 10 second intervals). For the AWACS/EAGLE system, two measurements each from the passive IRSS and the active laser-ranger are enough to quickly converge on an accurate ballistic trajectory estimate from which all potential cueing functions could be performed. An example of the tracking accuracy prediction for the EAGLE sensor suite is shown in Figure 8 for a 10 second target viewing interval. If required, comparable results can be obtained at faster rates (analyzed down to 2 seconds).

The performance shown in Figure 8 indicates that because of additional timely ranging data an equivalent passive IR sensor performance is far superior to a multiple-sensor stereo processing. A few very accurate range measurements from the co-aligned receiver yield a velocity estimate that can not be equaled by the stereo passive-only systems. The performance comparison is equally valid for boost-phase tracking. Not only earlier accurate track handover is possible, but 50–100 seconds improvement in the engagement timeline compared to other cueing methods affords the downrange active defense system greater intercept opportunities. For longer range TBM attacks, passive stereo tracking has a definite utility because of longer TBM flight times and the limited operational range of the laser-ranger.

3.5 Radar Cueing Performance

This analysis was performed using a computer tool, called "Radar Cueing Work Station (CWS)," originally developed for the Air Force Space Command to model space-based sensor cueing performance. A model for the AWACS/EAGLE system was generated, then the analysis tool was modified to have the radars accept a cueing from the airborne sensor platform. Results of the analysis are discussed below.

An assumed point defense interceptor and radar, similar to the Patriot PAC-3 and MPQ-53, benefits from an external cueing of the medium range (600 km) TBMs. The detection range improvement buys the weapon system an additional 100 second of the battle engagement time, as shown in Figure 9. However, the kinematic limit of the interceptor precludes any shooting advantage.

Benefits to an assumed area defense interceptor and radar, similar to THAAD/GBR, are highly scenario dependent. EAGLE cueing is useful against intermediate range and longer TBMs (>600 km).

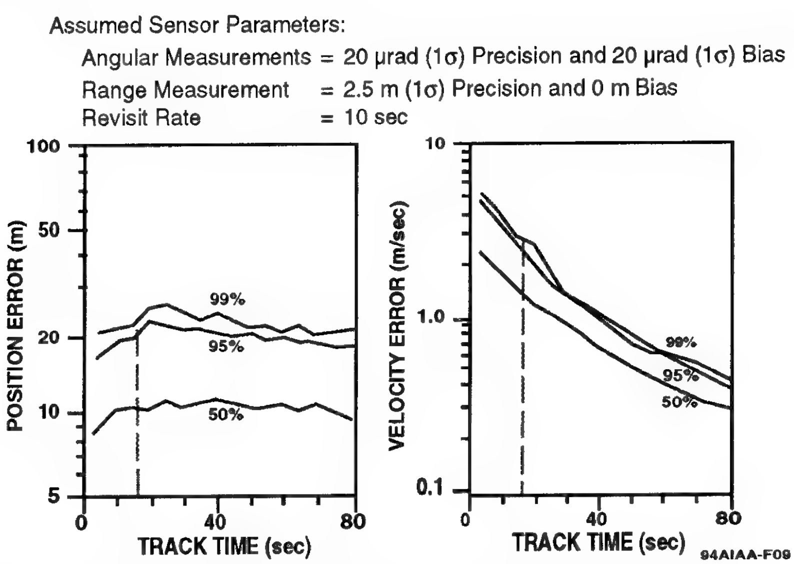


Figure 8. EAGLE System Tracking Performance at Time after Booster Burn-out

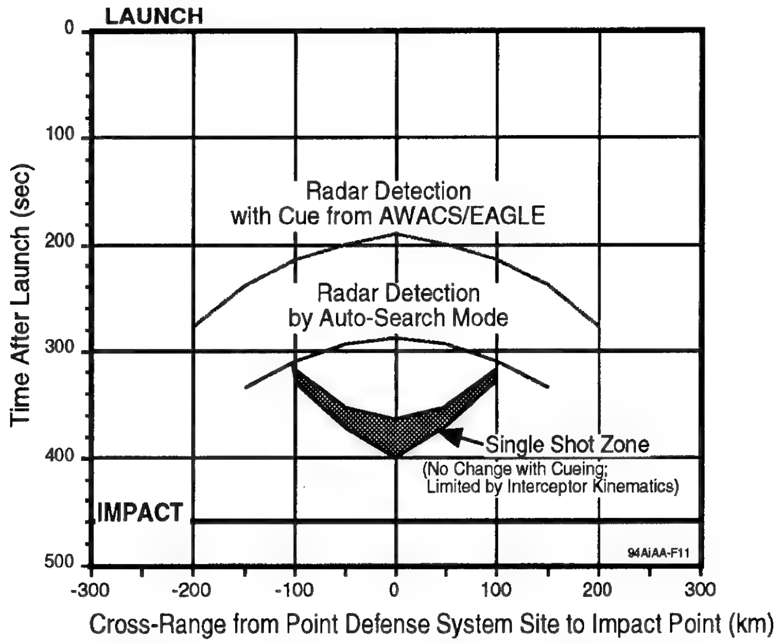


Figure 9. Point Defense System Detection and Intercept Opportunities against a 600-km TBM for Auto-Search Mode vs. Cueing from the AWACS/EAGLE

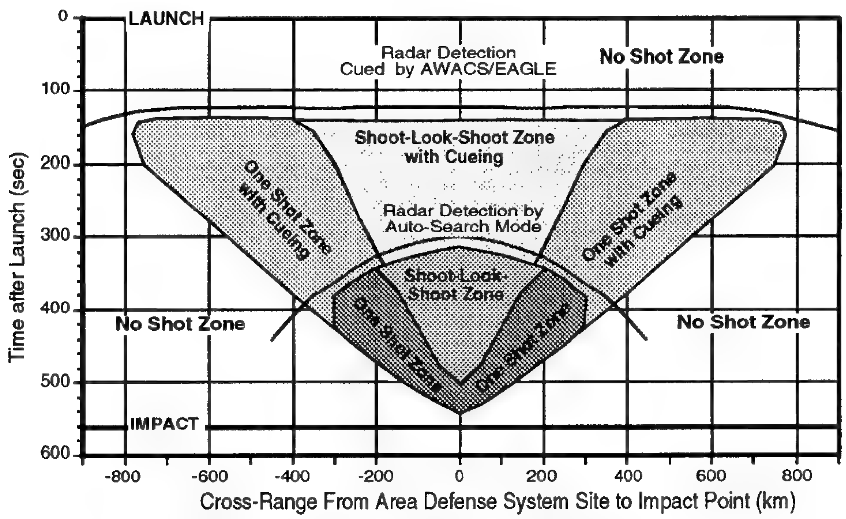


Figure 10. Area Defense System Detection and Intercept Opportunities against a 1000-km TBM for Auto Search Mode vs. Cued Mode

Cueing performance against intermediate range TBMs is impressive, as illustrated in Figure 10, since the missiles can be detected by the radar 200–300 seconds sooner, depending on the cross-range distance of the area defense system battery site to the intended TBM impact point. The interceptor engagement battle space increases significantly as shown in the figure. The interceptor engagement can take the full advantage of the increased timeline at these ranges. Also, one area defense battery site can defend against the intermediate-range TBMs impacting almost as far as ±800 km cross-range from the site with early cueing versus only ±300 km cross-range for no cue. This means that less weapon battery sites are needed to defend the same area. For North Korean campaign, No Dong Launches to Japan can be intercepted sooner and as few as three area defense battery sites are needed to defend most of Japan, while about a dozen batteries may be necessary without cueing. Similar analyses by others have reached the same conclusions. System benefits improve with longer range missiles. Because of additional surveillance and track time, passive only tracking becomes a feasible option in some limited engagements.

Although not analyzed, Naval systems such as the AEGIS AN/SPY-1 radar with an upper tier weapons system based on the LEAP interceptor technology may benefit the most from early cueing against medium to long range TBMs. Since the weapons are not limited by kinematics, every second of increase battle space afforded by a very early cue can be used to engage the targets.

4.0 SUMMARY

This paper has described the benefits of advanced TMD surveillance provided by the EAGLE airborne sensor suite designed for the AWACS platform. Precise, early knowledge of TBM trajectories affords TMD active defense weapon systems enhanced performance and flexibility.

Using an integrated passive/active sensor suite, EAGLE establishes a very precise and accurate track immediately after the booster burn-out, thereby increasing the active defense engagement battle space and enhancing the overall system effectiveness. Early broadcast of precise impact point predictions helps the BM/C3 system in attack assessment and enables passive defense elements to react sooner. Timely TBM launch point estimates aid the counterforce response.

The AWACS system is already an integral and very key asset for the theater battle campaigns as ably demonstrated during Desert Storm. The sensor technology for the EAGLE is readily in hand enabling development of the prototype and fielding aboard an AWACS platform to perform the TBMD Active Defense mission.

5.0 ACKNOWLEDGMENT

The authors would like to acknowledge the modeling and analysis assistance and critical review provided by our respective colleagues at BMDO, NRC (John Wentz, Mark Rivera, Dave Salazar, Jeff Skelton, and Dave Reed), and WJSA (Larrene Harada, and Mark Salazar). Notwithstanding, our timely administrative support by Ms. Anne Lietzan-Sanders and Linda Longerbeam was immeasurable and much appreciated.

During our efforts, we were invited to numerous technical reviews and conferences (e.g., ESC/AWD, AFSMC, and HQ ACC/DRT), where many views on this system and directly related TBMD topics were shared with us. We express our thanks to those who provided us with insight and appreciation for potential capabilities and design options.

This analysis effort was funded by the BMDO under contract SDIO84-92-D-0002 and SDIO84-94-C-0008. The views expressed are those of the authors, and do not reflect the official policy or position of the U.S. Government.

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Infrared and millimeter wave detection using thin films of Pb doped BiSrCaCuO superconductor

L. Ngo Phong
Defence Research Establishment Valcartier
P.O. Box 8800, Courcelette, QC G0A 1R0, Canada

ABSTRACT

Thin film detectors made of CuO superconductors were developed in our laboratory. This article reports details of the fabrication and testing of Pb doped BiSrCaCuO detectors. The detector comprises a film sensor housed in a small cryostat with built-in bias supply and temperature control circuitry. The film sensor was first deposited by magnetron rf sputtering and then crystallized under a rapid thermal annealing process. The characteristics of the response of the detector under millimeter wave and infrared illumination were investigated. The millimeter wave response exhibited a Josephson component with a $D^* \sim 10^8$ - 10^9 cm.Hz$^{1/2}$/W in the wavelength range of 3 - 8 mm. The transient response to short pulses indicated a time constant $\tau \leq 10$ ns for this component. The response to laser pulses was thermal in origin and inherently compressible, preventing saturation of the detector electronics to intense beams. The wide band characteristic of the responses at both infrared and millimeter wavelengths could be confirmed. The damage threshold of the film sensor was shown to exceed 10 mJ / cm^2 per 3 ns pulse. The possible use of these detectors for threat detection and the optimization of their figure of merit are discussed.

I. INTRODUCTION

The worldwide arsenal of radar- and laser-aided weapons is growing in numbers and sophistication. The recent advances in tunable sources with sufficiently high power densities led to the requirement for an extended band width of future threat classification and localization devices. A solution to increasing the effective wavelength band of the latter devices is to combine the use of different detectors. In general, these detectors have dissimilar properties and operating requirements so that the design of a hybrid device may be complex. The use of a single wide band detector offers a simpler alternative. Furthermore, it is better suited to certain configuration designs for wavelength discrimination or direction finding. The efficiency of conventional wide band detectors, however, is limited either by their low speed and detectivity or by the liquid helium cooling requirement.

Superconductors can be used as wide band detectors under specific conditions. Fast sensitive responses have been demonstrated at infrared and millimeter wavelengths in thin films of low temperature BaPbBiO and Sn.[1,2] The sensing applications of the recent CuO superconductors with critical temperatures (T_c) above 77 K have, therefore, received considerable attention. In this work, the fabrication and testing of Pb doped BiSrCaCuO thin film detectors were specifically investigated. The relevant details of the device fabrication are described in section II. In sections III and IV the characteristics of the responses at infrared and millimeter wavelengths are presented and discussed. The main focus in the discussion of the results is on the identification of the detection modes from the response signatures.

II. DEVICE FABRICATION

The enhanced formation of the high T_c $Bi_2Sr_2Ca_2Cu_3O_{10}$ phase by the addition of lead was confirmed in our previous work.[3] To fabricate the sensing device with a high operating temperature, single target magnetron rf sputtering has first been used to deposit Pb doped BiSrCaCuO onto (100) $LaAlO_3$ or MgO substrates. The sputter target was manufactured under a solid state reaction of high

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

purity compounds of PbO, Bi_2O_3, $SrCO_3$, $CaCO_3$, and CuO. The stoichiometric weight of each compound *j* was

$$M_j = n_j \, \mu_j \, M_t \, / \, \Sigma \, (n_j \, \mu_j), \qquad (1)$$

where n_j is the number of moles required for achieving the nominal composition Pb:Bi:Sr:Ca:Cu = 2:2:2:2:3 of the target, μ_j is the molecular weight, and M_t, 35 g, is the weight selected for the target. These compounds were repeatedly mixed, ground, and sintered during 12 hours at 800 °C in air. The resulting homogeneous, well-reacted mixture was pressed at 140 MPa into a disk target with a diameter of 50 mm. The disk target was subsequently bonded to a copper base plate using silver epoxy. The copper plate served as a mechanical support and provided a better thermal conductivity between the target and the heat sink.

The rf sputtering deposition was performed in 4 mTorr of argon at a power level of 80 W. The distance between the target and the substrate table was 8 cm. The thickness and area of the substrate were respectively 200 µm and 1 cm^2. The substrates were mounted on the substrate table at a distance from 3 to 4.5 cm with respect to the discharge axis. In this range the deposition rate was established to be ~ 10 nm/min. The deposition time was controlled to produce films with thicknesses ranging from 200 to 1000 nm. The as-deposited films were amorphous and insulating as no intentional heating was applied to the substrates during the deposition. A short thermal annealing, first in oxygen and then in air, was necessary to form the superconducting phases. The temperature for annealing in oxygen ranged from 810 to 830 °C, and that in air from 830 to 870 °C. The annealing times were varied for different samples, with maxima of 20 and 40 min in oxygen and air respectively. The effects of annealing parameters on the film properties have been reported elsewhere.[4] In this work, mainly granular films of $Bi_2Sr_2CaCu_2O_8$ - $Bi_2Sr_2Ca_2Cu_3O_{10}$ multiphase were used since the Josephson detection was of primary interest. These films show typically a sheet resistance R_s ~ 24 Ω / □ at 300 K and a resistance transition in the vicinity of 100 K.

The film sensors were patterned into meander line

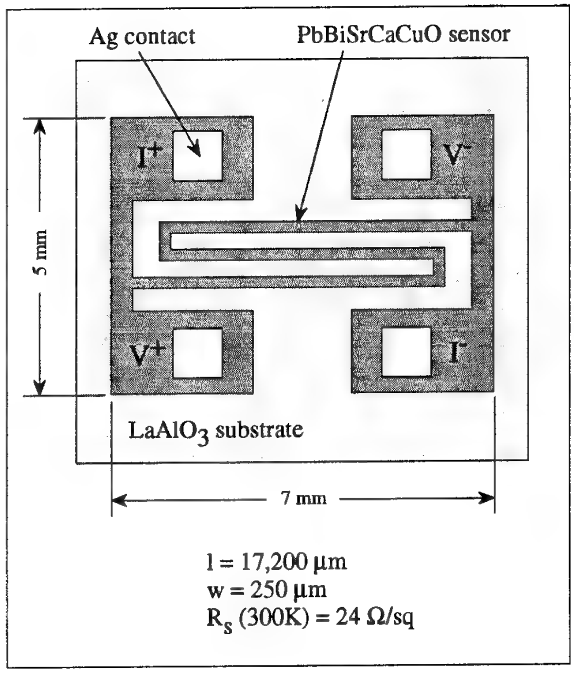

FIG. 1. PbBiSrCaCuO meander line sensor in four-terminal configuration.

structure with a length-to-width ratio l / w ~ 70. The patterning process was performed by first coating a 1-µm thick layer of positive photoresist onto the superconductor film. The film with the coated photoresist was exposed under ultra violet light for about 40 s with a photomask placed directly on it. The photoresist was subsequently developed in a solution for about 2 min and washed in de-ionized water. To remove the unwanted film areas, the sample was immersed in diluted HCl at room temperature for a period of about 10 s. After the etching, the sample was immersed in acetone to remove the photoresist on the superconductor pattern. Once done, an Al mask was placed in direct contact to the film with the four square windows aligned to the four rectangular contact pads in the pattern. The electric contacts to the sensor were formed by vacuum evaporation of Ag. The resulting superconductor sensor is schematically shown in Fig. 1.

In order to construct the detector unit, the sensor was thermally anchored to the cold finger of a small liquid nitrogen cryostat with photon access via a ZnSe window. The infrared and millimeter wavelength transmittances of this window were measured to be ~

0.9 and 0.7 respectively. The sensor temperature was first monitored by a Si sensor imbedded in the cold finger and then relayed to a feedback controller circuit. This circuit set the sensor temperature to the desired value by adjusting the thermal load of 2 high power transistors located on both sides of the sensor. The built-in bias supply consisted of standard 3 V lithium cells providing dc currents of up to 20 mA in the sensor through a variable resistor. The voltage signal generated across the sensor was driven to an rf amplifier with a band width of ~ 500 MHz and a gain of ~ 30 dB. All detectors have a bnc output connector and are terminated into 50 Ω. A 500 MHz digitizing oscilloscope with a resolution of 500 ps was used to record the voltage signals. A lock-in amplifier was occasionally used to detect the rms voltage fluctuation under modulated cw illumination or dark condition (noise). The voltage sensitivity of the lock-in amplifier was set at 0.1 nV for a frequency of 5 kHz. For the purpose of recording the resistance-temperature characteristics of the detector, a nanovoltmeter was also used to measure the output dc voltage.

III. MM-WAVE DETECTION

The millimeter wave was generated by different Gunn diode oscillators operating in the frequency band from 35 to 90 GHz (λ = 8.6 to 3.3 mm). The maximum cw power P_T of this source was measured to be ~ 70 mW. The main component of the millimeter wave was transmitted to the superconductor detector from a pyramidal horn antenna. The gain of the antenna of height H and width W was estimated as

$$G_T(\lambda) = 4\,\varepsilon\,\pi\,H\,W\;/\;\lambda^2, \qquad (2)$$

assuming an aperture efficiency $\varepsilon \approx 50$ %. Typically, G_T is ~ 25 dB at λ = 8.6 mm. With the far field condition $z > 2\,W^2 / \lambda$ satisfied, the power density p of the radiation incident on the detector could be evaluated,

$$p\,(\lambda) = P_T\,G_T\;\eta\;/\;4\,\pi\,z^2, \qquad (3)$$

where z is the separation between the antenna and the detector, and η denotes the transmittance of the ZnSe window at wavelength λ. The millimeter wave source could be operated either in cw or pulsed mode. In cw operation mode the incident radiation was amplitude modulated into square wave pulses with a 50% duty cycle. This was done by using a wave form generator which drives the electronics control of the Gunn diode. The pulse at this generator was further relayed to the lock-in amplifier so that the modulation frequency f served as a reference frequency in the detection. In pulsed operation mode the pulse at the wave form generator was transmitted to a broadband p-i-n switch in the waveguide through a driver. The p-i-n device provided a relatively fast switching of the incident wave so that pulses with a width as narrow as 30 ns could be produced. To characterize the transient power of the incident wave, a portion of it was driven to a fast GaAs point contact detector via a directional coupler.

It was previously established [5] that the interaction between millimeter wave photons and superconductors may lead to two principal response modes, hereby referred to as bolometric and nonbolometric modes. In the bolometric mode, radiation induces a temperature rise δT in the superconductor film sensor by lattice heating. When the sensor is current biased at a given temperature in the resistance transition region, this results in an increase δR of the bias resistance which produces a voltage change δV across the sensor. If δT is small compared to the transition width, then the responsivity r of a sensor with an active area S can be expressed as

$$r = I\,\delta R\;/\;\alpha\,p\;S \approx I\,(\partial R/\partial T)\;\delta T\;/\;\alpha\,p\;l\,w, \qquad (4)$$

where I is the dc bias current and α is the power absorbance. This equation provides insight as to the specific behavior of the bolometric responsivity. It suggests, for instance, that the temperature dependence of r is similar to that of $\partial R\,/\,\partial T$, provided that any variation of δT and α in the temperature range considered can be neglected. A deviation from this behavior may be indicative of a nonbolometric mechanism such as the Josephson detection. However, no conclusion can be drawn from this criterion alone.

To envision the effect of operating temperature, in Fig. 2 the responsivity r of a representative detector to

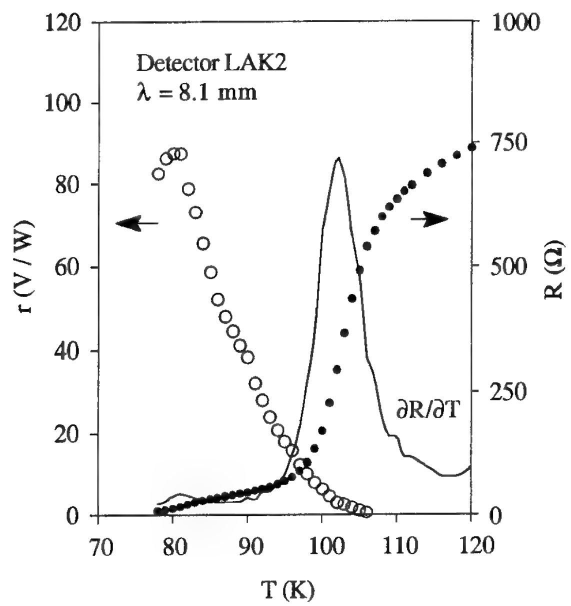

FIG. 2. Left vertical scale (open circles): temperature dependence of the mm-wave responsivity, I = 2.5 mA, f = 100 Hz. Right vertical scale (solid dots): resistance-temperature characteristic of the detector measured at I = 2.5 mA. The solid line shows the temperature variation of $\partial R/\partial T$.

modulated 8.1-mm cw radiation is plotted versus T. Here, r denotes the rms value of δV normalized to the cw power delivered onto the sensor assuming $\alpha = 1$. The detector was biased at I = 2.5 mA. Its R - T characteristic at the same magnitude of I and the corresponding temperature dependence of $\partial R / \partial T$ are also shown. We noted that the superconductor sensor exhibits a $T_{onset} \sim 110$ K and a $T_c \sim 77$ K, which are indicative of the constituent $Bi_2Sr_2CaCu_2O_8$ - $Bi_2Sr_2Ca_2Cu_3O_{10}$ multiphase. This rather broad transition suggests also a strong granularity of the device. As the sensor is first biased into a partially resistive regime where $\partial R / \partial T$ values are small, r is seen to reach a peak value at T = 80 K. With T increasing further to about 106 K at which $\partial R / \partial T$ peaks, r decreases by contrast to the noise level. It appears from this discrepancy that the behavior of r (T) deviates from that predicted by the thermal model. Further disagreement with the thermal model stems from the fact that the responsivity of ~ 90 V / W measured at T = 80 K is many times larger than the largest possible value of bolometric responsivity. In effect, the upper bound on the bolometric responsivity could be estimated as follows. After a haft cycle period $t = 1 / 2f$ the maximum heat energy received by the sensor is $\in = p / 2f$, assuming full absorption and neglecting any cooling. The temperature increase due to heat storage within a diffusion length $\xi \approx (Dt)^{1/2}$ in the sensor of specific heat c and thermal diffusivity D is

$$\delta T = \in / c\,\xi = (p / c)\,(t / D)^{1/2}. \qquad (5)$$

To evaluate more precisely δT we need to compare the thermal diffusion length ξ to the sensor thickness υ. Using typical values of thermal conductivity[6] ($k \approx 10^{-2}$ W / cm K) and specific heat[7] ($c \approx 0.9$ J / cm^3 K) around T_c for BiSrCaCuO, the diffusivity constant was estimated to be $D \approx k / c = 1.1 \times 10^{-2}$ cm^2 / s. It follows that $\xi >> \upsilon$ for f = 100 Hz, where $\upsilon \approx 400$ nm. Since the absorbed heat was assumed to be confined in the sensor during the period t, the value of υ is taken for ξ_{max}. Therefore, according to Eqs. (4) and (5) the bolometric responsivity should not exceed

$$r_{max} \approx I\,(\partial R / \partial T) / 2 f c\,\upsilon\, l\, w. \qquad (6)$$

Referring to Fig. 2, the magnitude of $\partial R / \partial T$ can be derived to be ~ 3.3 Ω / K at T = 80 K, yielding $r_{max} \approx$ 26 V / W. This value is seen to be much smaller than the measured responsivity despite the assumption that the heat energy was totally absorbed and confined in the sensor. Since a bolometric component may contribute negligibly to the overall response in the vicinity of T_c, this response is believed to be predominantly nonbolometric.

Further support to the nonbolometric origin of the response stems from the observation that the rms value of δV remained unchanged as f was increased. Whereas the detector exhibits a square law response to low power radiation, that is, $\delta V \propto p$, the above observation clearly shows that δV is independent of heat energy delivered to the sensor. Moreover, the transient voltage response of the sensor was observed to reproduce the square wave pulse of the cw radiation, indicating that it has a short time constant. To confirm the high speed detection of the superconductor sensor, its response to short millimeter wave pulses was investigated. Figure 3 shows the transient voltages of both incident and detected signals

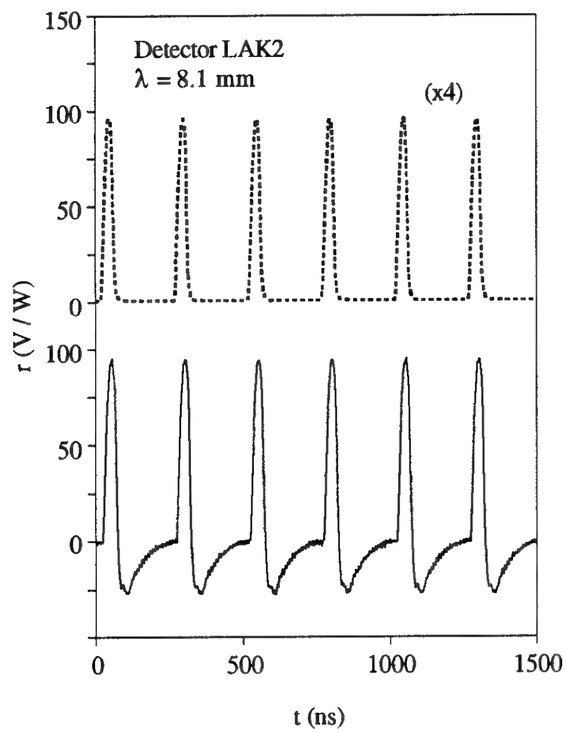

FIG. 3. Top (dotted line): incident millimeter wave pulses recorded by a GaAs point contact detector, the responsivity of which was magnified 4 times for comparison. Bottom (solid line): corresponding transient response of a PbBiSrCaCuO detector at T = 80 K and I = 1.5 mA.

as normalized to the peak power generating each signal. At a repetition frequency of 4 MHz, the incident pulses were recorded with a fast GaAs point contact detector and detected simultaneously with the PbBiSrCaCuO detector. The latter detector was biased at T = 80 K and I = 1.5 mA, where its responsivity is seen to be about 4 times larger than that of the GaAs detector. The rise time t_r, fall time t_f, and pulse width Δt of the incident and detected pulses are compared in Table I. It can be seen that, except for a small difference in pulse width, the temporal structure of the incident pulse could be reproduced with the superconductor detector. The response time τ of this device, defined as the recovery time of the response signal from 100 % to 36 % of its amplitude, was measured to be less than 10 ns. As compared to the diffusion time $t_d \sim \upsilon^2 / D$ for heat propagation through the film sensor along c-axis, τ is approximately 15 times shorter. Such a response speed is too fast to be consistently attributed to a thermal mechanism. Another

TABLE I. Time constants of incident and detected millimeter wave pulses. The incident pulses were characterized with a GaAs point contact detector and detected with a PbBiSrCaCuO detector operating at T = 80 K and I = 1.5 mA.

	Incident pulse	Detected pulse
$t_{r\,10\%\text{-}90\%}$ (ns)	17.6	17.6
$t_{f\,90\%\text{-}10\%}$ (ns)	11.2	11.2
$\Delta t_{50\%}$ (ns)	31	33

feature that rules out this mechanism is the large responsivity of the detected signal. After a pulse period $t = \Delta t$ = 30 ns the thermal diffusion ξ can be estimated to be inferior to the sensor thickness υ. Combining Eqs. (4) and (5), the maximum bolometric responsivity

$$r_{\max} \approx I\,(\,\partial R\ \ /\,\partial T\,)\ (t\ /\ D)^{1/2}\ /\ c\ l\ w, \qquad (7)$$

yields $r_{\max} \sim 200\ \mu V / W$ in this case. As anticipated from the short heating period, this value is excessively small compared to the detected signal amplitude. This observation, again, comfirms the occurrence of a nonbolometric detection mechanism under the conditions used in this study. Also noted in Fig. 3 is a secondary pulse component with reversed sign in the detected signal. Its origin has not been identified. Although the secondary pulse appears to have a large time constant, it also shows a large responsivity. The latter fact, in precise analogy to the above, excludes the bolometric mechanism as being responsible for the observed anomaly.

Since the observed nonbolometric response mode occurred solely in granular film sensors, the Josephson detection appears to be the most likely mechanism. A granular sensor may be modeled as an array of superconducting grains interconnected via Josephson junctions or weak links. This model assumes that the macroscopic response results from a superposition of the response signals of individual junctions forming the network. A discussion on this model has been given elsewhere.[5] In this work, we could further confirm the Josephson detection in the wavelength range from 3 to 9 mm. Figure 4 shows the wavelength dependence of the detectivity D^* of a PbBiSrCaCuO detector at T = 80 K and I = 2.5 mA. The detectivity

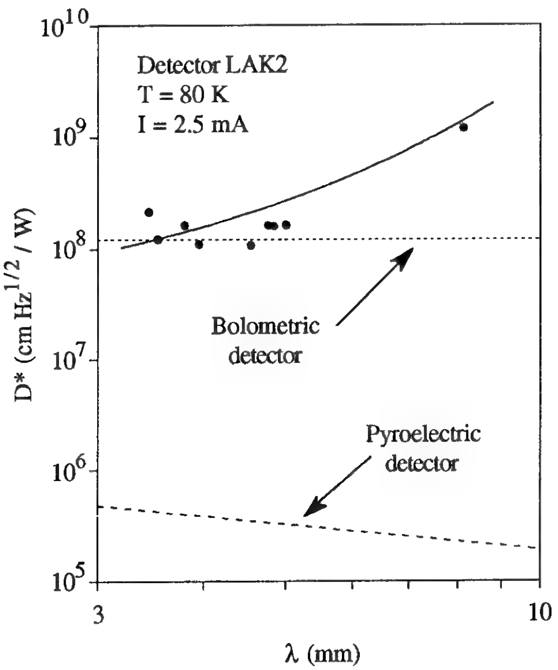

FIG. 4. Wavelength dependence of the detectivity of a PbBiSrCaCuO detector at f = 5 kHz. The solid line is provided as visual aid. The detectivities of a bolometric detector (S = 0.2 cm^2; τ = 35 μs; dotted line) and a pyroelectric detector (S = 0.03 cm^2; τ = 10 ms; dashed line) are also plotted for comparison.

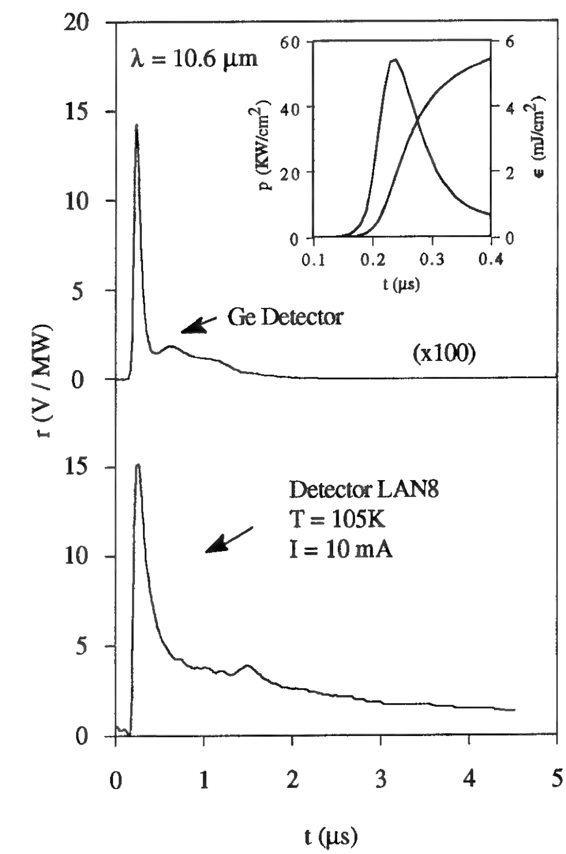

FIG. 5. Top: incident CO_2 laser pulse recorded by a Ge photon drag detector, the responsivity of which was magnified 100 times for comparison. Bottom: corresponding transient response of a PbBiSrCaCuO detector at T = 105 K and I = 10 mA. The inset figure shows the laser power density and fluence incident on the PbBiSrCaCuO detector on a smaller time scale.

was estimated from the noise measurement,

$$D^* = (S \,\Delta f)^{1/2} \, r \,/\, V_n \,, \qquad (8)$$

where $V_n \approx 20$ nV at f = 5 kHz and Δf = 2.45 Hz. Although the detector parameters and operating conditions have not yet been optimized, detectivities above 10^8 cm Hz$^{1/2}$ / W were obtained for λ in the range of 3 - 5 mm. At λ = 8.1 mm, the detectivity was evaluated to exceed 10^9 cm Hz$^{1/2}$ / W. These levels of D^* compare favorably with those of low speed, wide band detectors such as bolometric and pyroelectric [8] detectors. It should be recalled that the variation of α (λ) was not accounted for in the evaluation of r in Eq. (4). As a consequence of the assumption α = 1, the estimated values of D^* may be significantly smaller than the actual values. Furthermore, the wavelength dependence of the estimated D^* cannot be attributed to that of the Josephson responsivity alone. The increasing values of D^* at longer wavelengths appear, however, to be consistent with the λ^2 dependence of the Josephson responsivity. If this dependence holds for microwave frequencies, an increase of 1 - 2 orders of magnitude of D^* in this range may be anticipated.

IV. INFRARED DETECTION

As for millimeter wave photons, the interaction between infrared photons and superconductors may lead to a bolometric and a nonbolometric response mode. The bolometric mode results from the same temperature dependence of the sensor resistance as previously described. On the other hand, the mechanism of the infrared nonbolometric mode may differ from that responsible for the millimeter wave response. As the order parameter reported for $Bi_2Sr_2CaCu_2O_8$ films [9] is ~ 25 meV, infrared photons may cause dissociation of Cooper pairs and produce

TABLE II. Time constants of incident and detected CO_2 laser pulses. The incident pulses were characterized with a Ge photon drag detector and detected with a PbBiSrCaCuO detector operating at T = 105 K and I = 10 mA.

	Incident pulse	Detected pulse
$t_{r\ 10\%\text{-}90\%}$ (ns)	40	41
$t_{f\ 100\%\text{-}36\%}$ (ns)	70	250
$\Delta t_{50\%}$ (ns)	85	210

excess quasiparticles. Due to the resulting decrease of the relative fraction of Cooper pairs to quasiparticles, the Josephson critical current in the film is reduced. If the film is biased by a current close to the critical value, a fast voltage change will be induced under infrared illumination. In order to determine whether such a nonbolometric detection mode occurs in the fabricated detectors, their responses to short laser pulses were measured at different infrared wavelengths. The preliminary results of this study are described in this section.

In Fig. 5 the transient response of a PbBiSrCaCuO detector to 10.6-μm laser pulses is shown together with the laser pulse characteristic. The infrared source consisted of a TEA CO_2 pulsed laser with a beam diameter of about 2 mm at the output. A Ge photon drag detector was used to characterize the laser pulse. This detector has a responsivity of ~ 0.14 V / MW and a time constant smaller than 1 ns when terminated into 50 Ω. The power density p and fluence ∈ of laser pulse incident on the superconductor sensor were measured to be about 54 kW / cm^2 and 15 mJ / cm^2 respectively. To facilitate the analysis of the result, the superconductor sensor was patterned into a bridge with an active area slightly larger than the beam size. The thickness of the sensor was 240 nm.

There are several features of the transient response of the PbBiSrCaCuO detector which suggest that it is rather predominantly thermal in origin. We first noted an increase of phase shift between the incident and detected signals, both of which simultaneously recorded, when the operating temperature T was decreased at temperatures below T_c. The observed time delay may correspond to the period of heat delivery required for increasing the sensor temperature from T

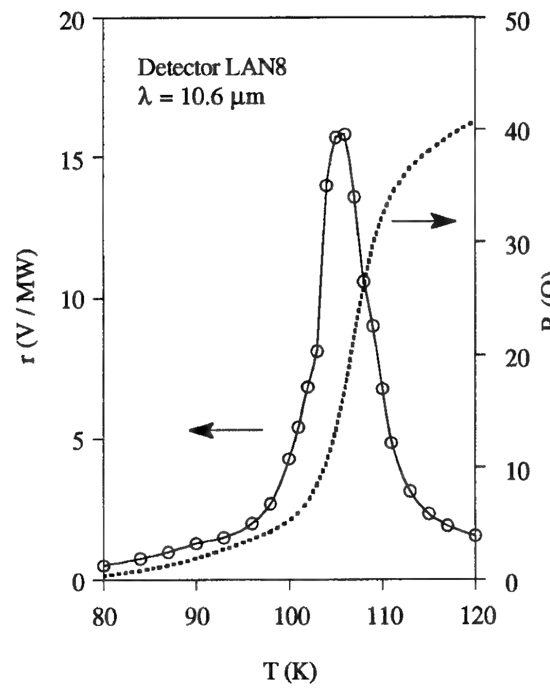

FIG. 6. Left vertical scale (open circles): temperature dependence of the responsivity to CO_2 laser pulses, I = 10 mA. Right vertical scale (solid dots): resistance-temperature characteristic of the detector measured at I = 10 mA. The solid line is provided as visual aid.

to ~ T_c where a response can be induced. Another relevant fact is the relatively slow recovery time of the transient response. Table II presents a comparison of the transient characteristics of the incident and detected pulses. Whereas the rise time remains unchanged for both pulses, the recovery time of the detected pulse is about 3.5 times larger than that of the incident pulse. Despite this difference, the time constants of the superconductor detector are seen to be small compared to those of conventional thermal detectors. This result may be partly attributed to the small thickness of the sensor.

Figure 6 illustrates the temperature dependence of the responsivity r and resistance R of the superconductor detector. Here, r denotes the peak voltage of the response signal, normalized to the peak power of the laser pulse incident on the sensor. Again, the behavior of r (T) is seen to be in good agreement with the thermal model described in Eq. (4) with δT ~ 0.7 K. At $T \approx$ 105 K where ∂R / ∂T peaks, r also reaches its maximum value which, referring to Fig. 5, is about 2

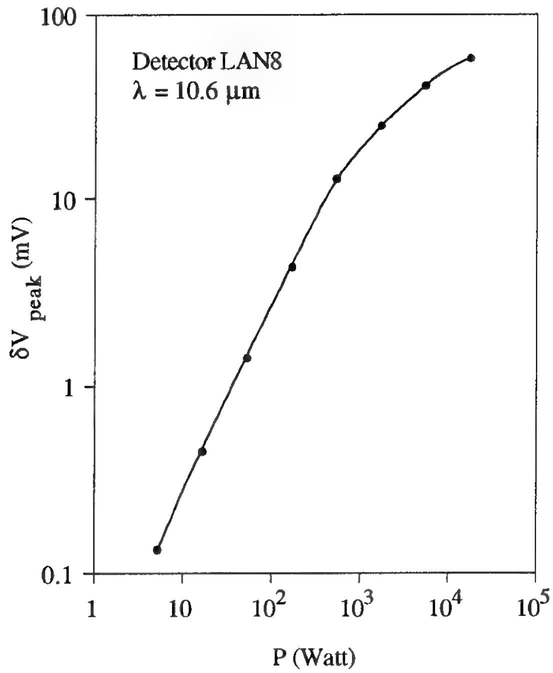

FIG. 7. Peak voltage response to CO_2 laser pulse as a function of laser power incident on the PbBiSrCaCuO detector, T = 105 K, I = 10 mA. The solid line is provided as visual aid.

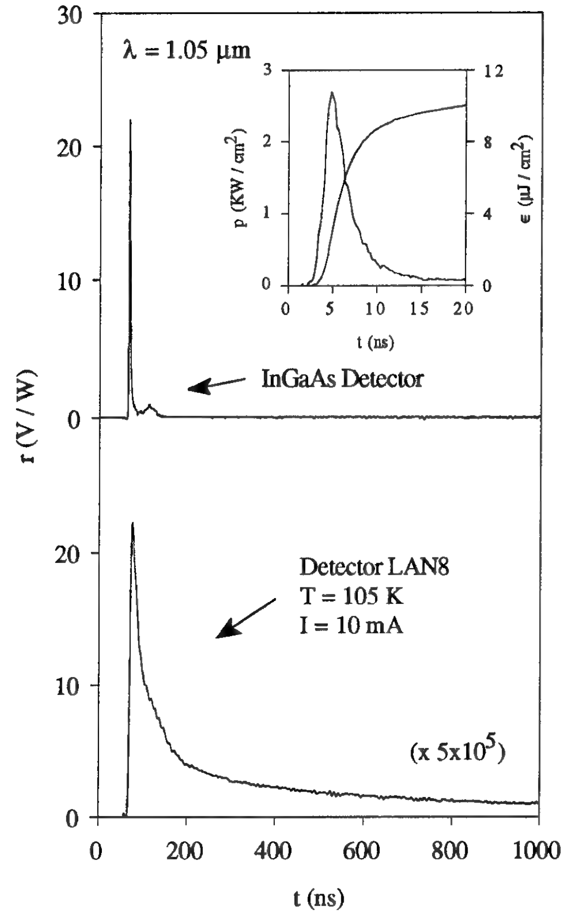

FIG. 8. Top: incident Q-switched Nd:YLF laser pulse recorded by an InGaAs detector. Bottom: corresponding transient response of a PbBiSrCaCuO detector at T = 105 K and I = 10 mA. The inset figure shows the laser power density and fluence incident on the PbBiSrCaCuO detector on a smaller time scale.

orders of magnitude larger than the responsivity of the Ge detector.

As a direct result of its thermal origin, the infrared response of the superconductor detector is inherently compressible. This characteristic can be illustrated as follows. When the sensor is biased at an operating temperature T in the transition region, the voltage response can be expressed as

$$\delta V_1\,(T) \approx I\,[\,R\,(\,T + \delta T\,) - R\,(\,T\,)\,]. \qquad (9)$$

For simplicity, assuming that by doubling the power density p of the laser pulse the temperature increase δT attains twice its initial value, so that the voltage response becomes

$$\delta V_2\,(\,T\,) \approx I\,[\,R\,(\,T + 2\,\delta T\,) - R\,(\,T\,)\,]. \qquad (10)$$

Referring to the R - T characteristic in Fig. 6, it can be seen that $\delta V_2 \approx 2\,\delta V_1$ within the linear region of the transition, and $\delta V_2 < 2\,\delta V_1$ when $T + 2\,\delta T > T_{onset}$. It follows that, even if a linear relation between δT and p can be maintained, the one between δV and p is nonlinear for large values of p. Figure 7 presents the power dependence of the voltage response of a superconductor detector operating at T = 105 K and I = 10 mA. As the laser power delivered to the sensor is increased by 10 dB, from 1.6 to 16 kW approximately, δV is seen to increase by only 3.6 dB. Such a compressible response makes it possible to prevent saturation of the detector electronics under illumination of high power lasers.

The characteristics of infrared detection given above could be further confirmed at shorter wavelengths. Figure 8 shows, for example, the transient response of the superconductor detector to 1.05-μm laser pulses, together with the laser pulse characteristic. The infra-

TABLE III. Time constants of incident and detected Nd:YLF laser pulses. The incident pulses were characterized with an InGaAs detector and detected with a PbBiSrCaCuO detector operating at T = 105 K and I = 10 mA.

	Incident pulse	Detected pulse
$t_{r\,10\%\text{-}90\%}$ (ns)	2	5
$t_{f\,100\%\text{-}36\%}$ (ns)	3	50
$\Delta t_{50\%}$ (ns)	3	28

red source consisted of a Q-switched Nd:YLF laser with a beam diameter of about 2.5 mm at the output. In order to characterize the laser pulse, an InGaAs detector with a response time of ~ 500 ps was used. The power density and fluence of laser pulse incident on the superconductor sensor were ~ 2.7 kW / cm^2 and 10 μJ / cm^2 respectively. Under this condition, the responsivity was evaluated to be r ~ 45 V / MW when the superconductor detector was biased at T = 105 K and I = 10 mA. The transient response of the latter device is seen to exhibit a relatively slow recovery after completion of the single laser pulse. The rise time, fall time, and pulse width of this response, as shown in Table III, are many times larger than the time constants of the incident pulse. As for the previous case, these results again suggest a predominantly bolometric origin of the observed response. The absence of the nonbolometric response under the conditions of this study may be attributed to different causes. One possible cause is the large thickness (~ 240 nm) of the film sensor. In a thick film, since the recombination time of the quasiparticles is much shorter than the diffusion time, the nonbolometric signal induced within the absorption depth may be short-circuited by the superconductivity of the dark portion of the film.

In order to assess the potential of using the PbBiSrCaCuO detector as a high power detector, the surface damage threshold of the film sensor was further evaluated. Due to the difficulty in correctly comparing different microstructures of granular polycrystal films, the change in the film resistance R after an exposure to laser irradiation was instead considered as an indication of surface damage. The damage threshold value was defined to be one order of magnitude below the value of incident fluence above which R is modified. The Q-switched Nd:YLF laser whose output characteristic was given in Fig. 8 and Table III was used as radiation source in this experiment. For a 200-nm thick sensor, the surface damage threshold measured at T = 300 K was ~ 10 mJ / cm^2 per 3 ns pulse for a pulse repetition frequency of 1 kHz. This relatively large value shows that PbBiSrCaCuO sensors can inherently withstand high power laser beams being used intentionally to defeat them. Subsequent testing of the exposed detector also confirmed that exceeding the threshold only degrades detector performance without causing complete failure.

V. CONCLUSION

PbBiSrCaCuO superconductor detectors were fabricated and characterized at millimeter and infrared wavelengths. The detector unit comprises a film sensor housed in a small cryostat with built-in bias supply and temperature control circuitry. The film sensor was first deposited by magnetron rf sputtering and then crystallized under a rapid thermal annealing process which controlled its operating temperature range. The millimeter wave response exhibited a fast Josephson component with a D^* ~ 10^8 - 10^9 cm.Hz$^{1/2}$ / W in the wavelength range of 3 - 8 mm. The response to short millimeter wave pulses indicated a time constant smaller than 10 ns for this component. The infrared response did not show nonthermal components under the conditions used in this work. Preliminary studies on the bolometric response to laser pulses confirmed the potential of PbBiSrCaCuO detectors for wide band detection of high power laser beams. These studies also established that the detectors can withstand fluences exceeding 10 mJ / cm^2 for 3 ns pulses and their response to high power pulses is inherently compressible.

The above results suggest that the developed devices may be useful as primary or complementary detectors in applications which require a wide band coverage in different spectral regions. Their figure of merit has not yet been optimized, meaning that the detector performance can be substantially improved. For example, the radiation absorbance can be enhanced by integrating the detector to a broadband antenna or by coating the sensor with antireflective layers. Also, work is under way to estimate the optimum parameters of

the film sensor including film thickness, granularity, and resistivity.

ACKNOWLEDGMENT

The author wishes to thank B. Tremblay for his technical assistance.

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OPTIMAL INFRARED DETECTOR CONFIGURATIONS FOR AIR TARGET DETECTION

G. Uda
G. Barani
Officine Galileo
Via A. Einstein, 35 - 50013 Campi Bisenzio - Florence
Italy

1. SUMMARY
The airtarget detection by a thermal camera is a typical problem of "hot spot detection" and the knowledge of the available energy on the infrared sensor becomes a critical item to analyse.In order to evaluate the performances of an infrared system in search and track, threat warning or passive surveillance, it is necessary to compute the Signal to Noise Ratio (SNR) of the system. The maximization of the SNR is an important goal to assure long detection ranges against stealth threats or cruise missiles with very low emissivities.The large number of detectors is just one of the requirements for this kind of applications and some energetic considerations lead up to consider particular geometrical array configurations. Usually, in the SNR evaluation it is assumed that all the energy from a target is focused by the optical system on a single detector element of the array. However, the image of a point source on the focal plane has a finite extent (spot) and its energy distribution is given by the Point Spread Function (PSF) of the optics.The interaction of the finite spot size with the array gives rise to a spreading of the energy impinging on the individul detectors, which causes a decrease of performances. In this paper a statistical evaluation of the loss of energy impinging on the detector due to the finite image size of point targets was performed through a Montecarlo simulation. By considering the maximum of the energy integrated by a single detector, it is possible to compute the effective SNR of the system. A new figure of merit, called Spreading Factor (SF), defined as the ratio between the maximum of the energy integrated by the single detector of the array and the total energy subtended by the PSF, permits to evaluate the capability of a detector array to detect point sources. Some typical detector and system configurations with their technological impacts have been examined.

2. INTRODUCTION
To evaluate the performance of an infrared system in "spot detection", it is necessary to compute the Signal-to-Noise Ratio (SNR). Usually, in the SNR evaluation it is assumed that all the energy from the target is focalized by the the optics on a single detector element of the array. However, it is well known that the image of the point source on the focal plane has a finite extent and its energy distribution is given by the Point Spread Function (PSF) of the optics. In order to evaluate an optimal detector configuration for "air target detection" application, it is necessary to take into account the interaction of the finite spot size with the array, because there is a spreading of the energy impinging on the individual detector and a corresponding decrease in performances occours and an average blur spot efficiency factor for this loss can be computed.
The aim of this work is to compute this loss factor and to compare some typical detector-optics systems, in order to define the optimal configuration for this kind of application, in each spectral waveband.

3. POINT TARGET DETECTION
If a point target is considered, the SNR directly depends on radiant intensity J of the target, and the radiant power incident on the detector can be written as (1) :

$$\Phi = \frac{J \cdot A_0 \cdot \tau_0 \cdot \tau_a(R)}{R^2} \qquad (1)$$

where :

A_0 - Area of the optical pupil
τ_0 - Optics transmittance
τ_a - Atmospheric transmittance
R - Range

When all the other parameters of the system are considered, the usual Signal-to-Noise Ratio is :

$$SNR = \frac{J \cdot A_0 \cdot \tau_0 \cdot \tau_a(R) \cdot D^*}{R^2 \sqrt{A_d \cdot \Delta f}} \qquad (2)$$

where :

D^* - Detectivity
A_d - Detector area
Δf - Equivalent noise bandwidth

4. EFFECTIVE SIGNAL-TO-NOISE RATIO
In the previous expressions it has been assumed that all the energy from the target is focalized on the single detector element; however if an optical system is composed by a circular aperture with uniform transmission, the image of a distant point source on the focal plane, is a finite size blur spot and the corresponding energy distribution is given by the Point Spread Function (PSF). If the system is aberration free, the irradiance distribution on the focal plane of a target having a radiant intensity J, is given by (2) :

$$P(m) = \left(\frac{2 \cdot J_1(m)}{m}\right)^2 \cdot \frac{J \cdot A_0 \cdot \tau_0 \cdot \tau_a(R)}{R^2} \cdot \frac{A_0}{\lambda^2 \cdot f^2} \qquad (3)$$

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

with:

$$m = \frac{\pi \cdot \sqrt{x^2 + y^2}}{\lambda \cdot F_\#} \quad (4)$$

where :

- J_1 - First Order Bessel function of the first kind
- λ - Average operating wavelength
- f - Focal length of the optics
- $F_\#$ - Focal number of the optics
- x,y - Coordinates in the image plane

The radius of the blur spot on the focal plane corresponds to the first zero of the PSF (the quadratic term in equation (3)):

$$r_0 = 1.22 \cdot \lambda \cdot F_\# \quad (5)$$

Figure 1 illustrates the relative position of the PSF on the focal plane and the interaction of the finite image size with the discrete structure of the detector array. In order to characterize an optimal detector configuration for spot detection, the energy loss due to relative positioning of the PSF, with respect to some different detector arrays, has been considered.
The detector configurations we have analyzed are :

- Scanning InfraRed Charge Coupled Devices (IRCCD) with charge integration
- Staring with and without microscanning
- Scanning without charge integration

4.1 SCANNING IRCCD WITH CHARGE INTEGRATION

In a scanning IRCCD array (fig. 2), each detector integrates the signal falling on it during the integration time τ_i and the corresponding displacement on the focal plane is given by:

$$\Delta x = v_s \cdot \tau_i \quad (6)$$

where v_s is the linear scan speed on the focal plane. It is important to note that for a fixed detector -optics configuration the product $v_s \, \tau_i$ must be a costant. If all the radiant power impinging onto the optics would be focalized on the single detector, the total energy collected after the integration stage could be written as:

$$E_{tot} = \tau_i \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x,y)dxdy = \frac{J \cdot A_0 \cdot \tau_0 \cdot \tau_a(R) \cdot \tau_i}{R^2} \quad (7)$$

However, if we choose a particular detector as a reference element, in the most general case the PSF will not be centered on this detector, because its axis is randomly shifted on the focal plane; therefore, the integrated energy must be written as:

$$E(x_s,y_s) = \frac{1}{v_s} \cdot \int_{x_s}^{x_s+v_s \cdot \tau_i} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x-x_0,y-y_s) \cdot rect\left(\frac{x}{a}\right) \cdot rect\left(\frac{y}{b}\right) dxdydx_0 \quad (8)$$

where :

- x_0 - Time dependent horizontal shift of the PSF ($x_0 = x_s + v_s t$)
- x_s,y_s - Starting horizontal and vertical shift of the PSF
- a,b - Detector width and height
- rect(z/w)- Rectangular function of z having width w

With these assumptions it is possible to define a factor η which gives the loss of energy due to the finite blur spot size and to its shift with respect to the detector:

$$\eta(x_s,y_s) = \frac{E(x_s,y_s)}{E_{tot}} \quad (9)$$

4.2 STARING ARRAYS WITH AND WITHOUT MICROSCANNING

In a staring array the scanning speed has not been considered, thus the integrated energy will be :

$$E(x_s,y_s) = \tau_i \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x-x_s,y-y_s) \cdot rect\left(\frac{x}{a}\right) \cdot rect\left(\frac{y}{b}\right) dxdy \quad (10)$$

Equations (7) and (9) are still valid.

4.3 SCANNING WITHOUT CHARGE INTEGRATION

In these detectors the integration time can not be considered, therefore the percentage energy loss reduce to the ratio between the following expression :

$$E(x_s,y_s,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x-x_s+v_s t,y-y_s) \cdot rect\left(\frac{x}{a}\right) \cdot rect\left(\frac{y}{b}\right) dxdy \quad (11)$$

and the expression :

$$E_{tot} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x,y)dxdy = \frac{J \cdot A_0 \cdot \tau_0 \cdot \tau_a(R)}{R^2} \quad (12)$$

The ratio η between equation (11) and (12), has to be performed when the spot is centered onto the reference detector to maximize the signal.

5. COMPUTER SIMULATION

Because equation (9) refers to a particular geometry PSF - detector, a Montecarlo simulation has been performed in order to evaluate the average of η, with respect to all the possible horizontal and vertical shift which maximize the SNR over the reference detector.
According to the particular detectors configuration, we have to define a region centered on the reference detector, where the PSF has the same probability of occurence (3).
In particular for a scanning IRCCD (fig. 3) the region is :

$$-\left(\frac{P_x + v_s \cdot t_i}{2}\right) < x < \left(\frac{P_x - v_s \cdot \tau_i}{2}\right)$$
$$-\left(\frac{P_y}{2}\right) < y < \left(\frac{P_y}{2}\right) \qquad (13)$$

where P_x and P_y are the horizontal and vertical pitch of the array, respectively . Note that for a staring array ($v_s = 0$), condition (13) reduces to:

$$-\left(\frac{P_x}{2}\right) < x < \left(\frac{P_x}{2}\right)$$
$$-\left(\frac{P_y}{2}\right) < y < \left(\frac{P_y}{2}\right) \qquad (14)$$

For a scanning detector without charge integration we have to define this region only in the vertical direction, because in the horizontal one we consider that the detection occurs when the spot is centered on the reference detector:

$$x = 0$$
$$-\frac{P_y}{2} < y < \frac{P_y}{2} \qquad (15)$$

By considering NRUN Montecarlo iterations, we compute the average SPREADING FACTOR (SF), for the particular optics and detector configuration which has been chosen.

$$SF = \frac{1}{NRUN} \cdot \sum_{k=1}^{NRUN} \eta(x_{s_k}, y_{s_k}) \qquad (16)$$

6. SYSTEM CONFIGURATIONS ANALYSIS

In order to evaluate an optimal detector configuration for "air target detection", a comparison among seven typical different systems , operating in the 3 - 5 and 8 - 12 μm wavebands, has been performed.
The parameters of the analyzed systems are summarized in the following table:

Tab. 1 - System characteristics

	Type	Material	Spectral Response [μm]	Det. size H x V [μm]	Pitch size H x V [μm]	D^* (peak) [cmHz^{½}W^{-1}]	F number	Int. time [ms]
System 1	*staring*	*InSb*	*3 - 5*	*40 x 40*	*50 x 50*	$5 \cdot 10^{11}$	*3*	*3.1*
System 2	*staring*	*InSb*	*3 - 5*	*30 x 30*	*38 x 38*	$5 \cdot 10^{11}$	*3*	*3.1*
System 3	*staring*	*PtSi*	*3 - 5*	*17 x 17*	*31.5 x 25*	$6.5 \cdot 10^{10}$	*1.8*	*3.1*
System 4	*staring*	*PtSi*	*3 - 5*	*16.5 x 16.5*	*25 x 25*	$6.5 \cdot 10^{10}$	*2.8*	*3.1*
System 5	*μscan* *	*InSb*	*3 - 5*	*40 x 40*	*25 x 25*	$5 \cdot 10^{11}$	*3*	*0.75*
System 6	*scanning IRCCD* **	*HgCdTe*	*8 - 12*	*25 x 28*	*43 x 28*	$7 \cdot 10^{10}$	*1.7*	*0.020*
System 7	*scanning without charge int.* ***	*HgCdTe*	*8 - 12*	*40 x 60*	*100 (linear array)*	$4 \cdot 10^{10}$	*3*	-

* *microscanning 2 x 2*
** *interlaced 2 : 1 and TDI = 4*
*** *interlaced 2 : 1 without TDI*

Geometrical configuration of system 6 and 7, are represented in fig 4 and 5, respectively

7. RESULTS AND DISCUSSION

In the following table are reported spreading factors corresponding to the previous systems, for a Montecarlo simulation with NRUN = 1000.

Tab. 2 - Spreading factors

Waveband	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	8 - 12 μm	8 - 12 μm
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
Spreading Factor	0.56	0.517	0.334	0.348	**0.88**	0.458	0.712

Tab. 3 - Signal to Noise Ratio without Spreading Factor

Waveband	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	8 - 12 μm	8 - 12 μm
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
SNR at 5 km	3845	**5127**	3818	779	1891	729	16
SNR at 10 km	602	**804**	599	122	296	56	1.3

Tab. 4 - Signal to Noise Ratio with Spreading Factor

Waveband	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	3 - 5 μm	8 - 12 μm	8 - 12 μm
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
SNR at 5 km	2152	**2651**	1277	271	1665	334	12
SNR at 10 km	337	**416**	200	42	261	26	0.9

To have a quick compendia, SF and SNR at medium range (5 - 10 km) are reported in tab. 2, 3, 4. Global results are represented in figure 6 ÷ 12, where SNR is shown vs range. For each spectral band we assumed a standard atmospheric condition with LOWTRAN 7 code (MIDLATITUDE SUMMER, RURAL EXTINCTION, VISIBILITY: 23 km) and a target radiant intensity of 50 W/sr .

Results concerning SNR have to be evaluated inside the respective spectral band, because the detectivity values have to be matched with the spectral exitance and with the atmospheric transmission coefficient across the band of interest. From tables and figures examination results that the system with highest Signal to Noise Ratio is number 2, irrespective of the SF value which reaches its maximum value on system # 5 (microscanning). In the 8 ÷ 12 μm band, the best SNR is obtained by the system #6 and the best SF by the system #7.

Results concerning "spot detection", state that system #2 is the optimal choice in the 3 ÷ 5 μm band, as well as system #6 is the best in 8 ÷ 12 μm band.

The importance of SF as a discriminating parameter in system evaluation clearly appears by the comparison between systems #1 and #3. Infact if the classical mathematical formulation of SNR is used, both the systems appear to have the same SNR value; otherwise if the SF is introduced, system #1 results to have better performances than system #3 of almost a factor 2 and thus in order to make a choice between different systems, a tradeoff between the standard mathematical SNR formulation and the SF value must be done.

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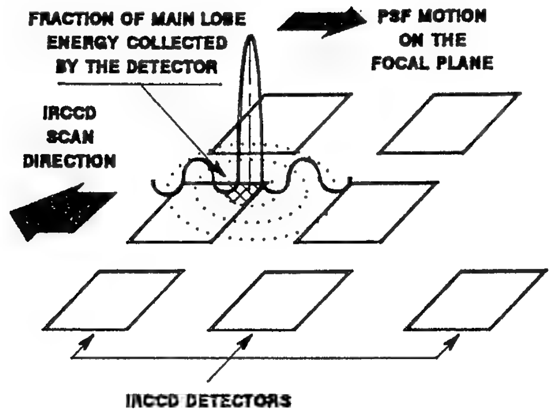


Fig. 1 - Relative motion of the Point Spread Function (PSF) on the focal plane

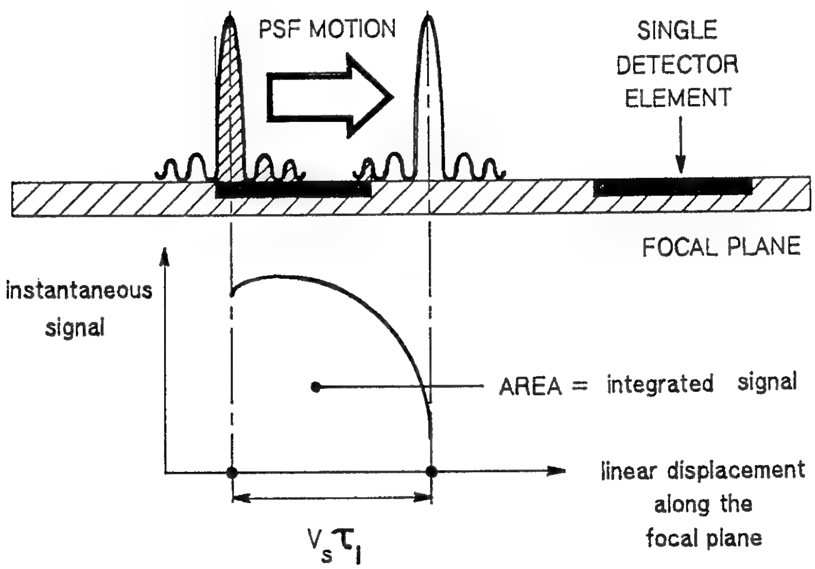


Fig. 2 - Integration of the instantaneous signal by an IRCCD

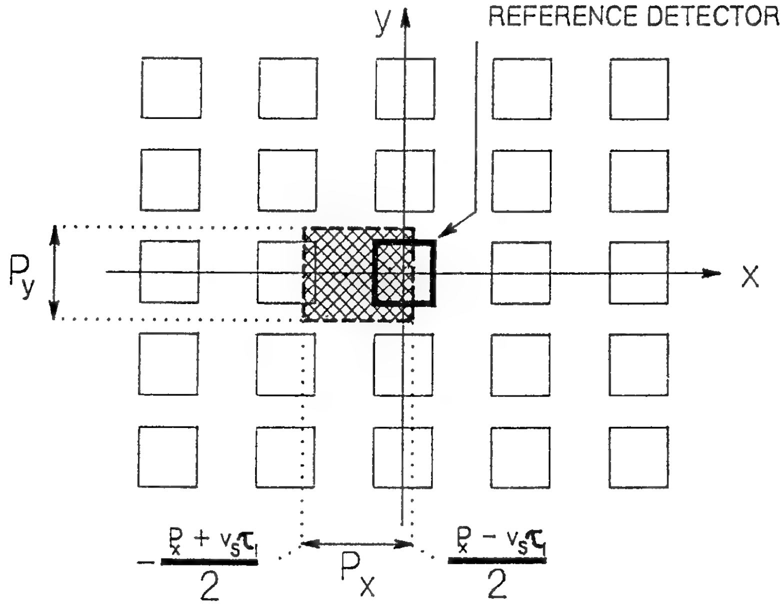


Fig. 3 - Starting position area on the reference detector

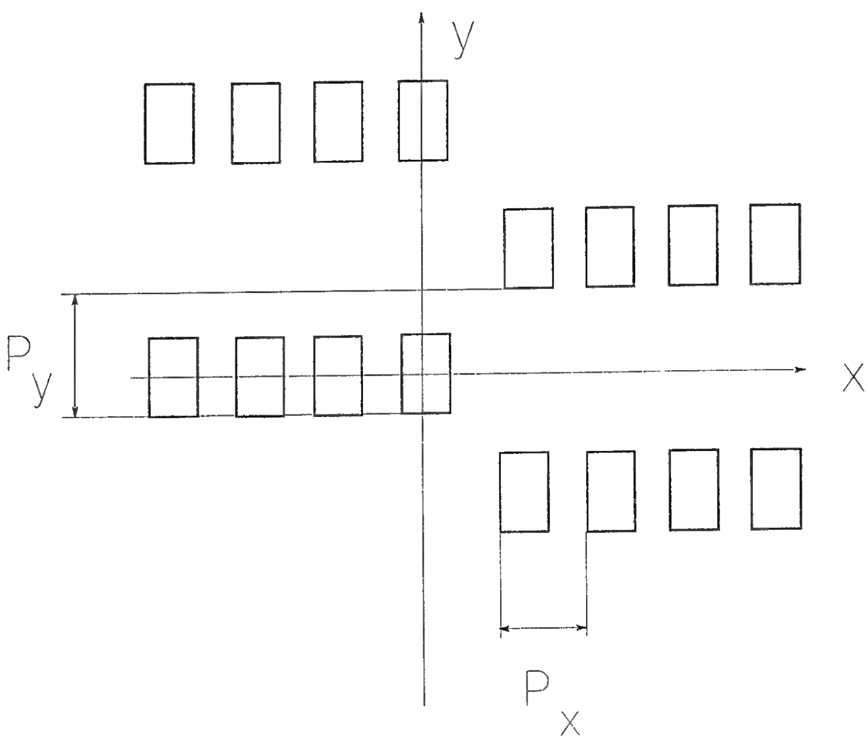


Fig.4 - Geometry of a scanning IRCCD with charge integration

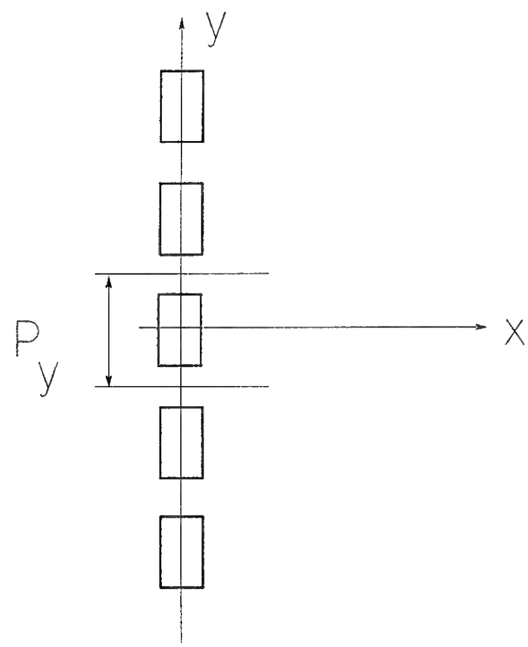


Fig. 5 - Geometry of a scanning detector without charge integration

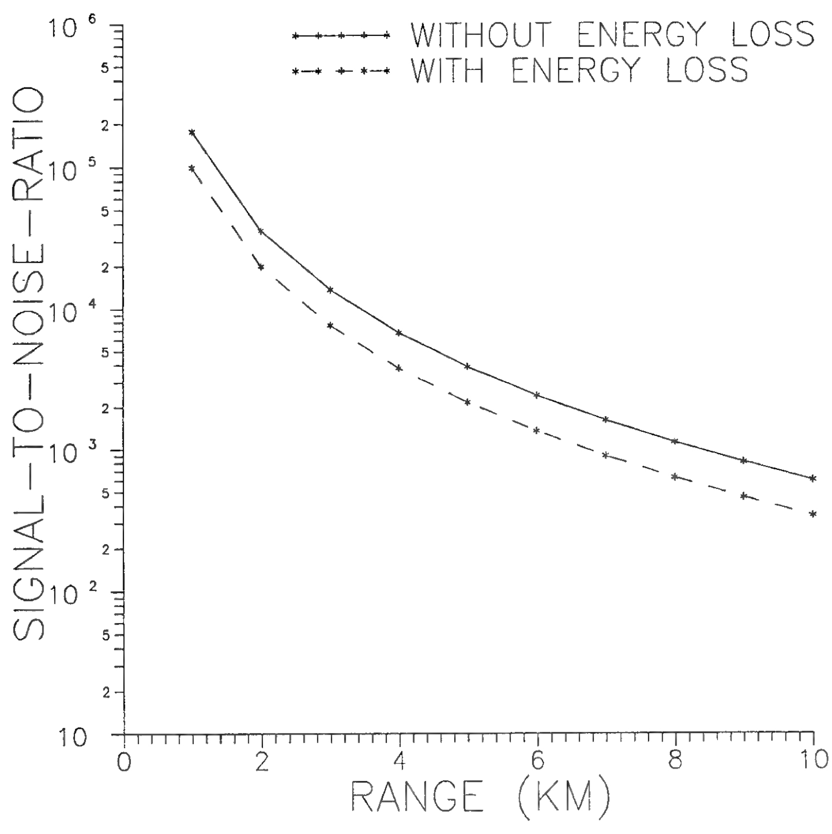


Fig. 6 - SNR vs Range for system #1 with (dashed) and without (solid) the SF

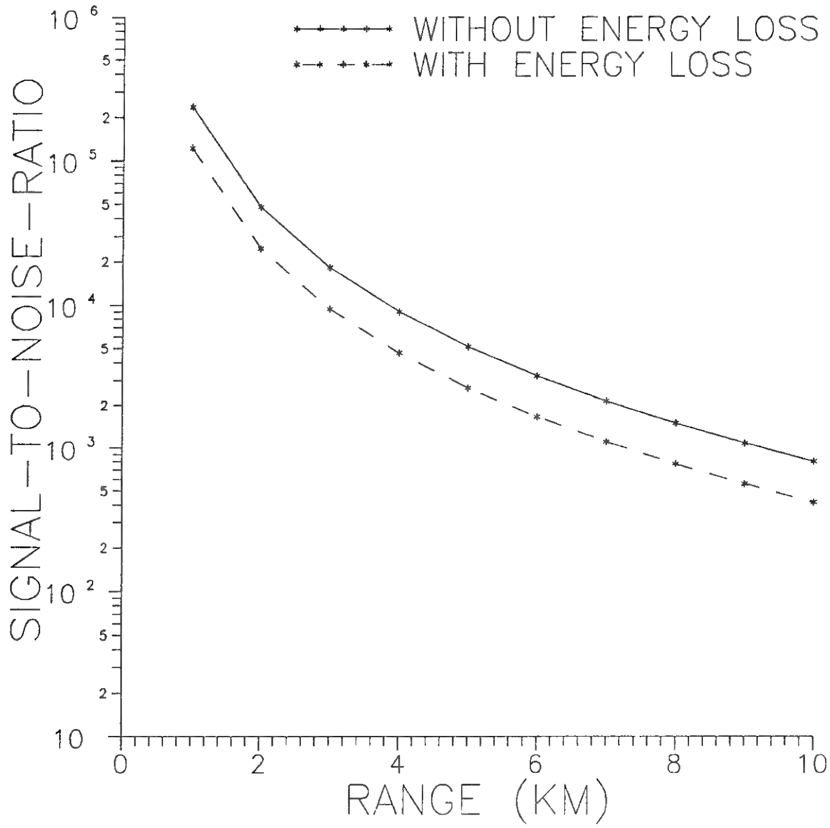


Fig. 7 - SNR vs Range for system #2 with (dashed) and without (solid) the SF

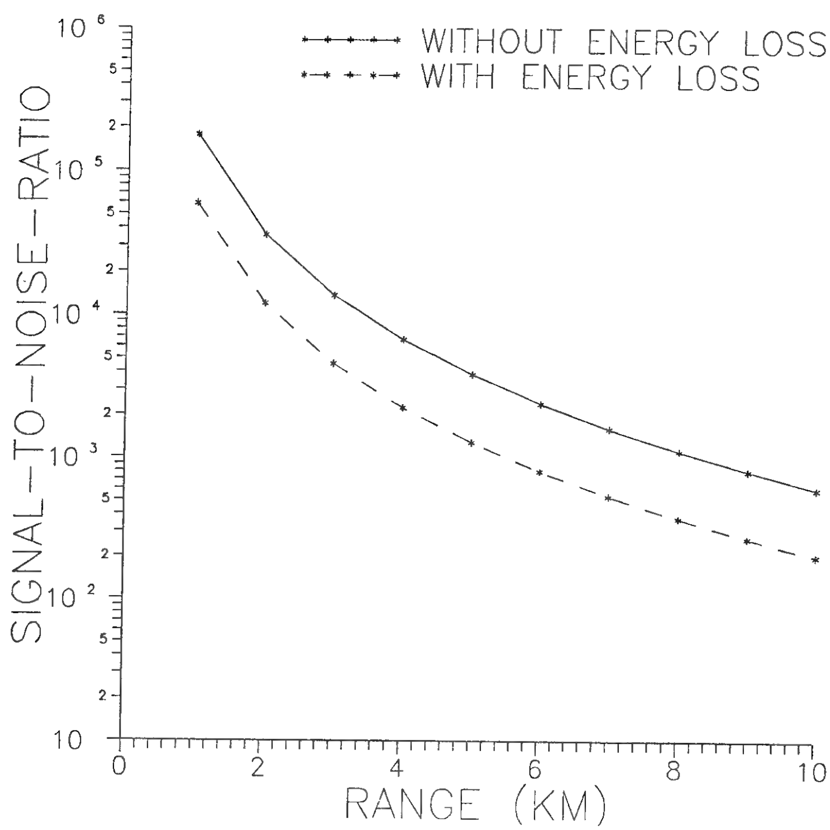


Fig. 8 - SNR vs Range for system #3 with (dashed) and without (solid) the SF

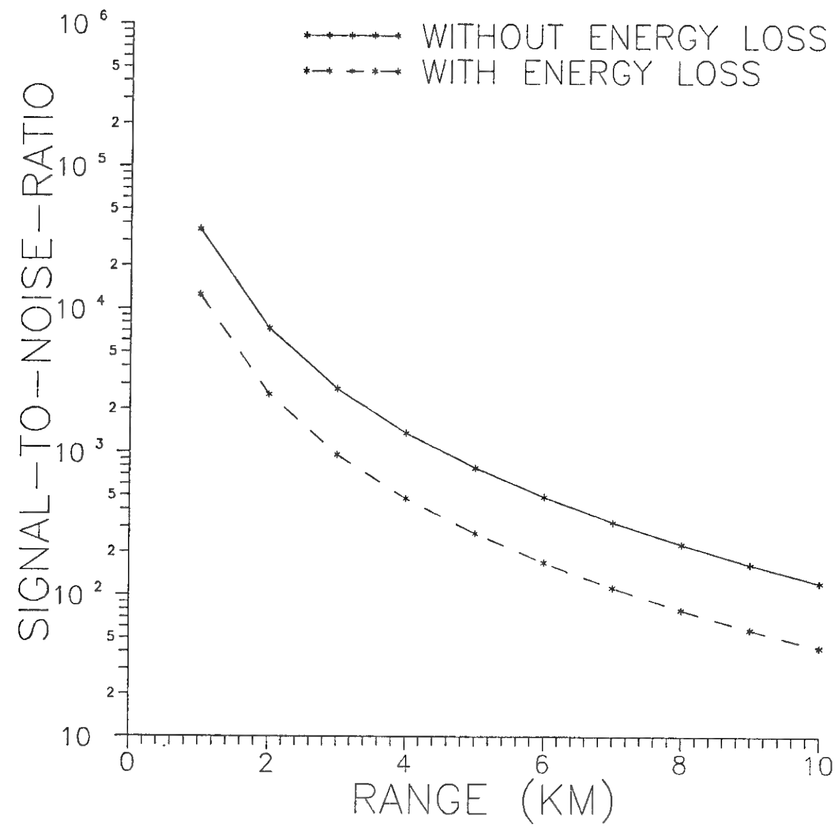


Fig. 9 - SNR vs Range for system #4 with (dashed) and without (solid) the SF

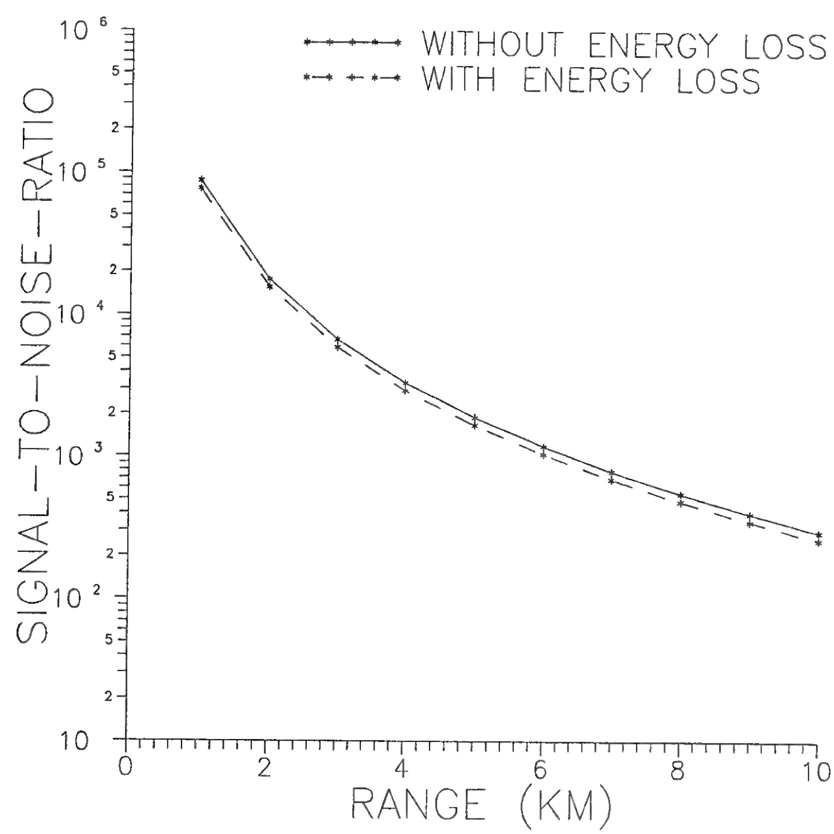


Fig. 10 - SNR vs Range for system #5 with (dashed) and without (solid) the SF

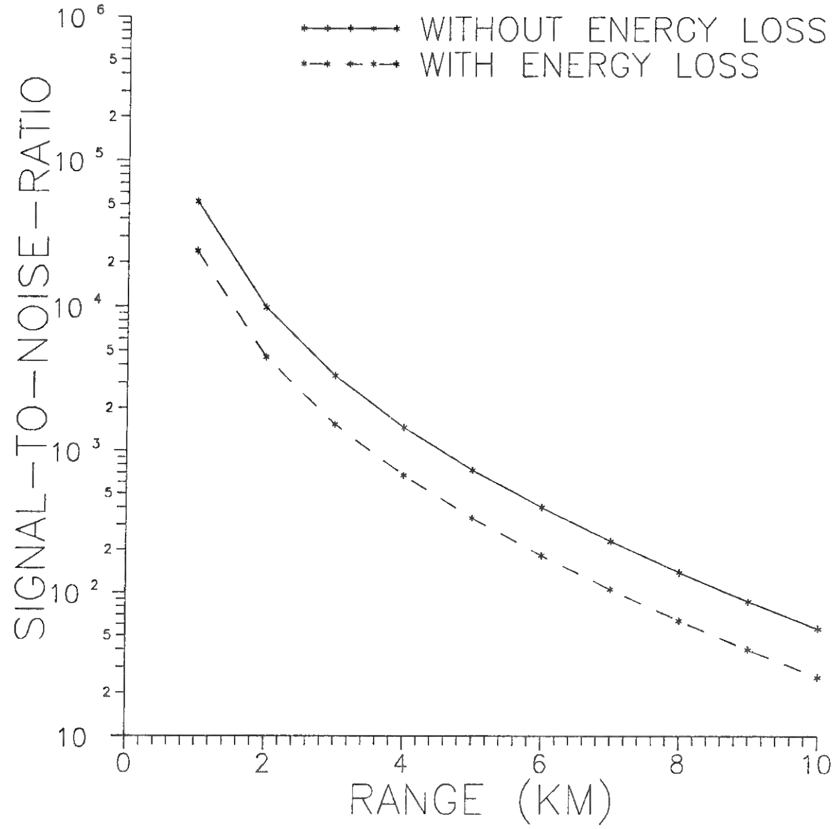


Fig. 11 - SNR vs Range for system #6 with (dashed) and without (solid) the SF

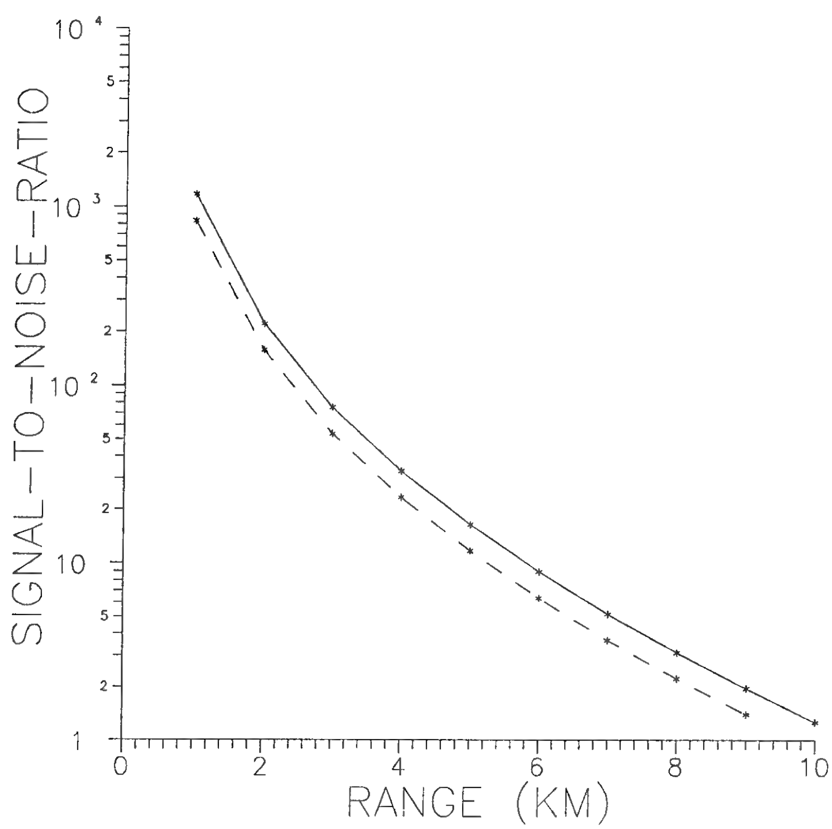


Fig. 12 - SNR vs Range for system #7 with (dashed) and without (solid) the SF

Acquisition, Tracking, Pointing and Fire Control for Ballistic Missile Defense

Thomas W. Humpherys, Col. USAF
Mr. Gary Gurski c/o Mr. L.C. Wolfe GRC
1900 Gallows Rd., Vienna, VA 22182 United States

1. INTRODUCTION

Desert Storm showed the political, psychological and military potential of SCUD type missiles in a theater conflict. Intercepting these missiles in their boost phase can dramatically reduce the chance of damage due to submunitions and limit the number of targets which must be handled by terminal defense systems like Patriot and THAAD. The key to the effectiveness of weapons for Boost Phase Intercept (BPI) is the development of precision acquisition, tracking, and pointing subsystems which enable BPI systems to perform the full range of defense functions: local surveillance and detection, tracking, target typing, target engagement, destruction and damage assessment.

There is an ongoing program in the Ballistic Missile Defense Organization to address Acquisition, Tracking, Pointing and Fire Control Technologies (ATP-FC). Over the past decade there have been dramatic advances in the component technologies for ATP-FC. The focus for this program has been Directed Energy Weapon systems development, such as high power lasers for air or space based systems. The program is currently entering a field testing phase to validate the technologies for boost phase intercept of Theater Missile Defense (TMD) targets.

Other Boost Phase Intercept (BPI) candidate weapon systems, such as kinetic energy weapons, appear to require many of the same technologies and supporting phenomenology as directed energy systems. This paper will describe the ongoing BMDO ATP-FC program and the potential utility of a balloon borne ATP testbed to support TMD testing.

2. ATP-FC PROBLEM

A BMD weapon system for boost phase intercept must include subsystems or components to perform the functions of finding and establishing the position of the targets, controlling the line of sight to the target and controlling the sequence of functions needed to manage the engagements of multiple targets in a short time. For a directed energy system, this means pointing a beam at a vulnerable location on the booster. For a kinetic energy weapon, this means pointing the interceptor so that it can strike the missile hardbody.

The following definitions of acquisition, tracking, pointing and fire control which will be used during this paper.

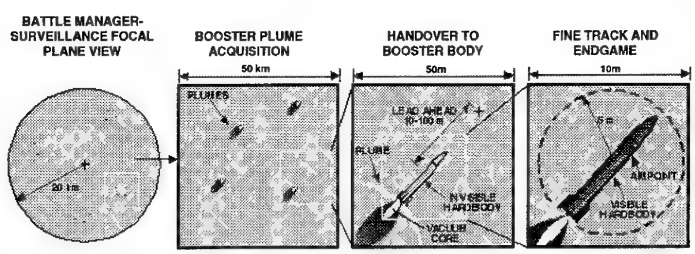
Acquisition of a target involves all of the sensing, processing, and control functions necessary to detect a target or target group and transfer the target location to the fine tracker.

Tracking is the ability to measure target/aimpoint position with sufficient accuracy to generate pointing commands to future target/aimpoint positions.

Pointing is the ability to maintain a reference line-of-sight direction to a target while following a target or targets at high angular rate.

Fire Control is the set of decision functions needed to engage a target or multiple targets in a short time.

To demonstrate the ATP process, consider the directed energy weapon boost phase intercpet example shown in Figure 1. Multi-target tracking requires optical sensors



- SEARCH AND ACQUIRE WITH ON-BOARD OR EXTERNAL SURVEILLANCE
- ESTABLISH AZIMUTH AND UNRESOLVED MULTIPLE TRACKS
- HANDOVER TO PLATFORM TRACKER

- PASSIVELY ACQUIRE SUBSET OF TARGETS AND TRACK TO < 50 m
- ESTABLISH TARGET TYPE
- HANDOVER TO SINGLE TARGET PASSIVE FINE TRACK

- PASSIVELY ACQUIRE SINGLE TARGET PLUME AND ESTABLISH TRACK TO < 10 m
- HANDOVER TO ACTIVE FINE TRACK
- IDENTIFY HARDBODY FROM PLUME
- ESTABLISH AIMPOINT

- ACTIVELY TRACK SINGLE TARGET TO << 1 m
- PROVIDE POINTING COMMANDS TO WEAPON
- ASSESS DAMAGE

DE ATP SYSTEMS ACHIEVE HIGH PRECISION TRACKING (<< 1 METER) WITH A HIERARCHAL SET OF FOCAL PLANES, EACH WITH NARROWER FIELD OF VIEW AND HIGHER RESOLUTION

Figure 1. Directed Energy Weapons ATP-FC Problem (Boost Phase Example)

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

with a large field of view. However, optical sensors cannot simultaneously provide sufficient resolution to locate vulnerable areas of the booster and maintain sufficient field of view to ensure rapid engagement of subsequent targets. As a result a series of sensors are required, each providing successively more accurate target location information. This series of sensors can be expected to operate over different spectral regimes (ultraviolet, visible and infrared) and be presented with varying target and background phenomenology effects.

The envisioned succession of sensors begins with the surveillance sensor as part of a battle management system. Surveillance is the process of identifying and locating a threat, in this case a group of boosters. The surveillance sensor may be located on a separate platform or on the weapon platform itself. This sensor must search a large area or a localized "threat area" and be capable of detecting multiple targets.

After the surveillance sensor has established an initial target state vector, it is passed to the platform acquisition coarse track (ACT) sensor which must identify the threat and begin the process of engaging individual targets. For the boost phase example, this is shown as the booster plume acquisition. These sensors will passively acquire targets within its field of view, track to an accuracy of less than 50m, establish the target type and handover the state vector of a single target to the passive fine tracker.

The passive fine tracker acquires a single target plume and processes to less than 10m track accuracy to identify the hardbody relative to the missile plume. This sequence is often referred to as hardbody handover.

Once the passive fine track is refined, the active illuminator is turned on, closed loop active track begins and track accuracy is rapidly reduced to fractions of a meter. Additional fire control processing establishes an aimpoint, assesses the damage and retargets the weapon systsem as required. This precision is sufficient to place a energy beam on the target or guide a kinetic intercept to hit the target.

3. ATP-FC ROLE FOR TMD

All Theater Missile Defense concepts are limited by common sensing and guidance issues. Theater missiles burn for only a few tens of seconds. To insure intercept in boost phase, missiles must be acquired soon after launch to support either launch of the interceptor or weapon beam turn on at the earliest possible time. In-track flight updates must be supplied for midcourse guidance and sensing must provide knowledge of the aimpoint to less than 1 m to ensure high probability of kill. Thus an integrated sensor/fire control solution must be developed for all weapon concepts. Sensing and fire control issues are substantially common for all hit to kill weapons. The principal differences are in the target phenomenology and timelines for committing the weapon.

The ATP-FC elements which must be addressed for boost phase TMD are illustrated in Figure 2 which shows the ATP-FC needs for kinetic energy and directed energy weapons. The shaded areas show the needs for these two weapon types. The central shaded area illustrates the substantial overlap in the technologies required for detecting missiles in a cluttered environment, extracting imaging information, early commit state estimation, and end-to-end fire control processing. The current BMDO ATP-FC program will address all the issues for directed energy ATP-FC. Since many of these issues are common to directed energy and kinetic energy, the BMDO ATP-FC program is capable of providing significant issue resoluition for kinetic energy systems as well.

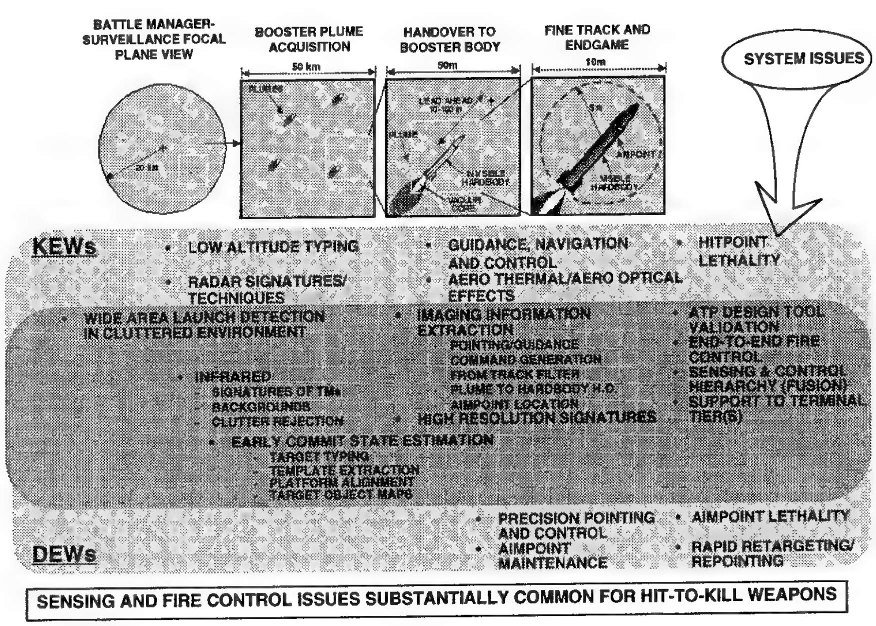


Figure 2. How ATP Plays In TMD (Boost Phase Illustration)

4. ATP-FC TECHNOLOGY STATUS

There has been significant progress in ATP-FC development during SDI, which was established in 1983 (see Figure 3). The ATP program has focused on four primary areas of performance: pointing and stabilization (the ability to stabilize a weapon beam while pointing at high angular rate); tracking (the ability to measure target/aimpoint position and generate pointing commands to future target/aimpoint positions); fire control decision functions (the ability to manage the engagements of multiple targets in a short time); and system integration (end to end functional compatibility from target detection to damage assessment and engagement of the next target.

The advances in several areas have been significant. The numbers next to the ovals indicate the magnitude of the performance improvement since the start of SDI.

The most dramatic advances have come in the area of pointing and stabilization where improvements have been as much as two orders or magnitude.

In the area of isolation/disturbance rejection, the Talon Gold ground experiment demonstrated scaled size pointing, boresight and alignment and disturbance isolation at the 100 nrad level. It utilized high bandwidth boresight and alignment techniques, fast steering mirrors for disturbance rejection and a magnetic suspension for disturbance isolation. The Space Active Vibration Isolation (SAVI) program demonstrated large capacity isolation at the 60-80db isolation level. SAVI technology was integrated into the 6m scale beam expander Space Pointing and Integrated Controls Experiment (SPICE). This laboratory structural pointing experiment recently demonstrated a disturbance rejection reduction ratio of 68:1.

In the boresight and alignment area, the Talon Gold brassboard demonstrated long term separate aperture alignment to 100 nrad and internal alignment to 20 nrad levels. The ARTS (Alignment Reference Transfer System), an optical system for transferring boresight between separate apertures, was fabricated and tested below the 100 nrad level.

In the inertial reference area, the current IPSRU (Inertial Pseudo Star Reference Unit) program is a 3 axis stabilized gyro system which is demonstrating significantly less than 100 nrad stabilization at 300Hz bandwidth.

In the fine pointing area, the relay mirror experiment (RME) successfully demonstrated beam stabilization and precision pointing of a laser from a ground site to the relay mirror on a satellite and back down to a ground target board at another location. Stabilization and drift levels were comparable to those required for full scale strategic directed energy systems.

In the area of long range tracking, the issues are best addressed as part of integrated field tests since they require the correct phenomenology and excellent pointing levels. Originally these were planned as part of space based experiments which have not been completed. The empty boxes indicate areas which require development and are now being addressed in the current ATP program. Relevant achievements in focal plane and processor component developments were sponsored in related programs outside of ATP.

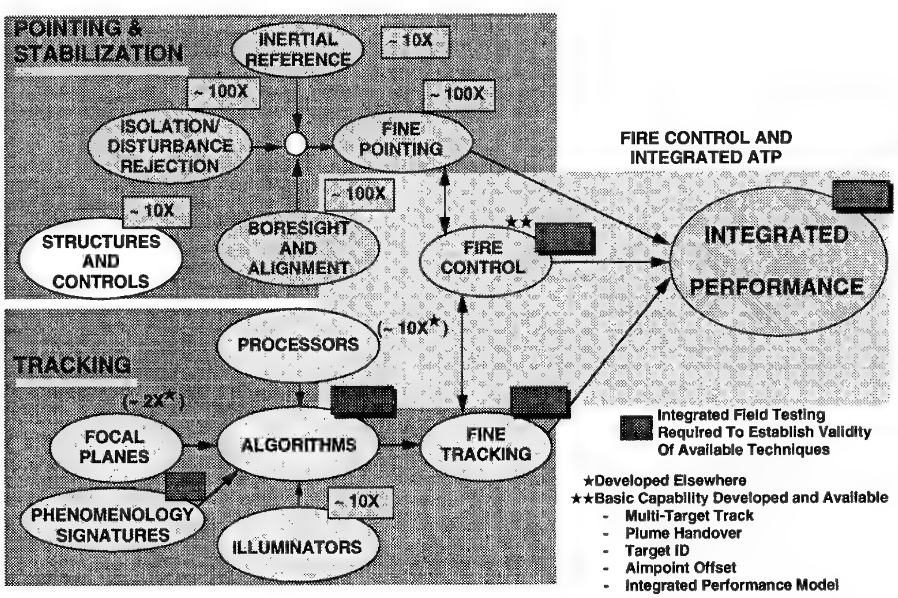


Figure 3. Dramatic ATP-FC Advances Since Start of SDI

In the area of illuminator development, a significant component development accomplishment has been achieved. The recently completed SSLRS (Solid State Laser Radar Source) program has provided a space system compatible laser illuminator at the 50W level designed for 60 pps operation.

In the area of fire control, first order algorithms and techniques for decision functions such as plume to hardbody handover and multi-target track have been demonstrated in computer simulations against real and synthetic data. The work to date has successfully established the feasibility of the required functions but has yet to establish their practicality and robustness in integrated field operation. This issue will be addressed in the balloon borne test platform for the current program.

Integrated performance has been delayed due to cancellation of space experiments. The current program is focusing on demonstrating integrated performance using a relatively inexpensive balloon borne ATP testbed. This effort will establish the validity of the available techniques.

5. ATP-FC PROGRAM ELEMENTS

The key and supporting elements of the ATP program are shown in Figure 4. The first of two primary elements of the program are the Advanced DEW Active Precision Tracker (ADAPT) program which will develop operational concepts, explore experiment options and resolve key integration issues for a spaced based, operational directed energy system. The ADAPT project includes analyzing and documenting technology scaling, developing design concepts and producing a development roadmap for an operational directed energy weapon system. In addition lab experiments will be used to investigate technologies for integration with a high power system such as an optical aperture sharing element. ADAPT contractors have demonstrated the feasibility of two different approaches to sharing the large telescope between the high power weapon beam and the precision tracker during high power operation. They have also developed designs for an ATP suite to be used in a future space based laser space integration experiment called StarLITE.

The second primary element is the High Altitude Balloon Experiment (HABE). HABE will be the primary means for conducting integrated end to end testing to validate ATP hardware, components and concepts. HABE includes a 60 cm multi-spectral active and passive ATP system suspended from a balloon. These experiments will address active and passive tracking issues against boosting targets. These tests, executed by the USAF Phillips Laboratory, are a very cost effective alternative to space-based testing.

Both ADAPT and HABE build upon the successes achieved in recent AT P accomplishments in technology programs and space experiments.

The Relay Mirror Experiment (RME), mentioned earlier, and the Low Power Atmospheric Compensation Experiment (LACE) were space experiments that feed into HABE. LACE flew a target board in low earth orbit and addressed atmospheric correction for lasers propagating from the ground. The platform also carried the ultra violet plume instrument (UVPI) which collected UV plume data for thrusting missiles.

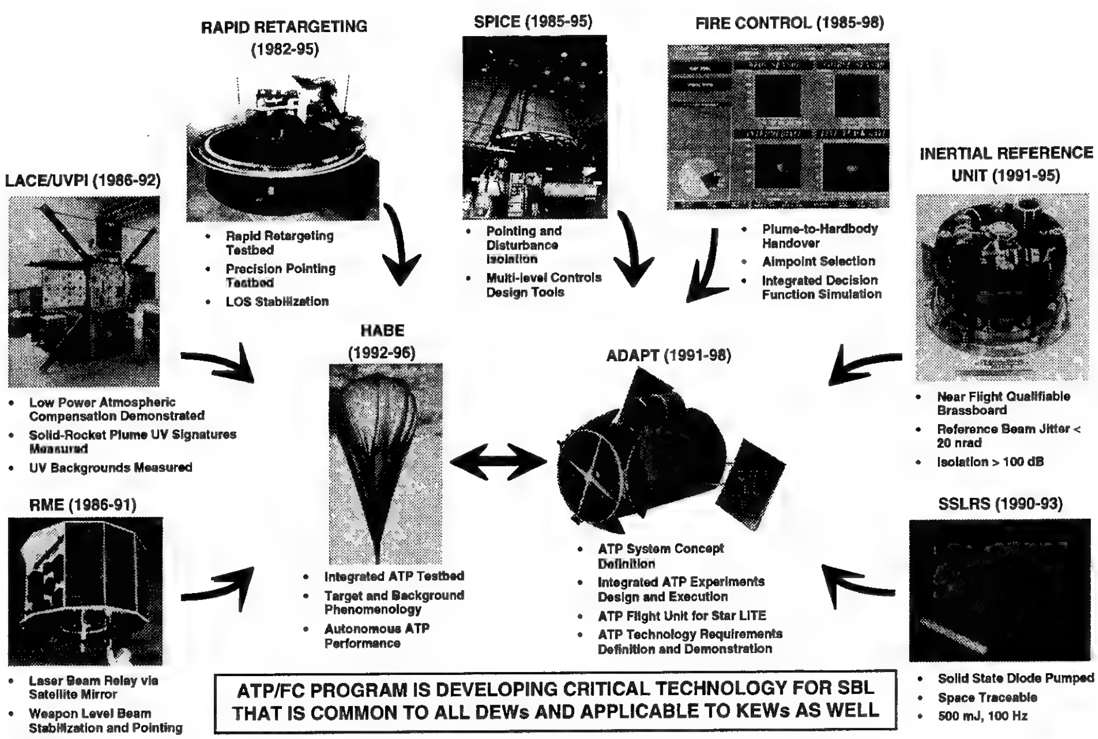


Figure 4. Acquisition, Tracking, Pointing and Fire Control

Two elements of the ATP program have addressed technologies for control and pointing of large structures.

The Rapid Retargeting Testbed provided an analog hardware simulation of large structures slewed over large retargeting angles. Modal avoidance and other techniques have been developed to maintain structural distortions within the operating range of the precision active alignment system employed in directed energy concepts.

The Space Integrated Controls Experiment (SPICE) completed a closed loop demonstration of active control of structural disturbances in a large, lightweight space structure. Jitter rejection ratios of 65:1 (ratio of base disturbance input to optical line-of-sight jitter) were achieved. By reducing 100 microradian jitter to less than 2 microradians, SPICE demonstrated that the large optical structures required by space based DEW can be controlled and isolated from satellite disturbances at levels approaching the performance requirements for an operational system.

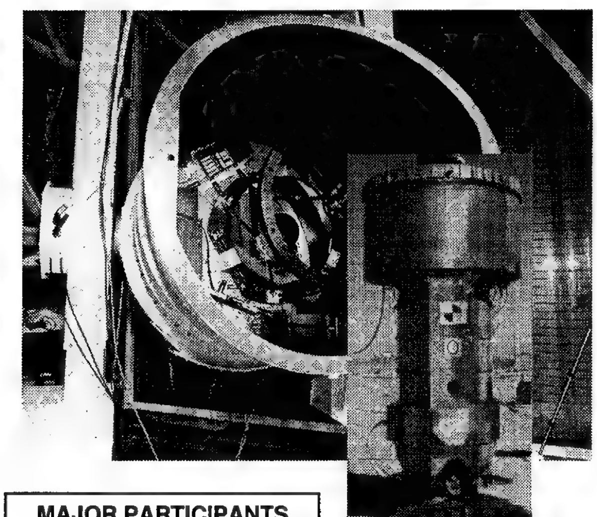
The Fire Control element contributes to HABE and ADAPT by developing fire control decision algorithms which will be tested on HABE and monitoring the development of end to end simulations and design tools which can provide analytic integration of all ATP components prior to detailed testing in experiments.

The Inertial Pseudo-Star Reference Unit (IPSRU) has been fabricated, assembled and tested. It is a high accuracy, 3 axis, flight qualifiable inertial reference unit that will provide the high precision stabilization needed for active track in the HABE ATP experiments. IPSRU meets unique DEW requirements for very low noise output signal over a wide band of platform angular rates and disturbance inputs. In FY93, IPSRU demonstrated stabilization to less than 100 nrad. An operational unit was delivered to HABE in March 1994.

The Solid State Laser Radar Source (SSLRS) program has recently developed a 50W solid state laser which will serve as the illuminator in the HABE active tracking tests. In FY93 the initial brass board system was reconfigured and packaged for compatibility with the HABE system. This instrument substantially improves the state-of-the-art for power output efficiency, and power-to-weight ratio for diode-pumped solid state lasers. This space qualifiable laser will be delivered to HABE in February 1994.

These elements are the tools which are available to address the common needs of directed energy and kinetic energy systems working against TMD targets.

Figures 5-9 give further details on each of the elements of the current program.



MAJOR PARTICIPANTS

PHILLIPS LAB

TECHNICAL OBJECTIVES

- DEMONSTRATE AND TEST CRITICAL INTEGRATED ATP-FC FUNCTIONS IN A REALISTIC ENVIRONMENT
  - Plume-to-Hardbody Handover
  - Line-of-Sight Stabilization And Disturbance Rejection
  - Point Ahead With Thrusting Target
  - Active Track Under Realistic Conditions
  - Autonomous, Acquisition and Tracking
- GATHER PASSIVE AND ACTIVE TARGET SIGNATURE DATA

TECHNICAL ACCOMPLISHMENTS/STATUS

- COMPLETED PDR, CDR, AND INITIAL FLIGHT SYSTEM GROUND TEST
- DEVELOPMENT PAYLOAD INTEGRATED INTO FLIGHT CANNISTER
- DEMONSTRATED PASSIVE CLOSED LOOP TRACK FROM GROUND AGAINST SCALED ROCKETS
- PERFORMING ACCEPTANCE TESTING FOR ILLUMINATOR AND INERTIAL REFERENCE UNIT

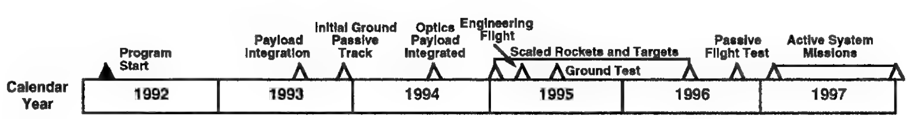
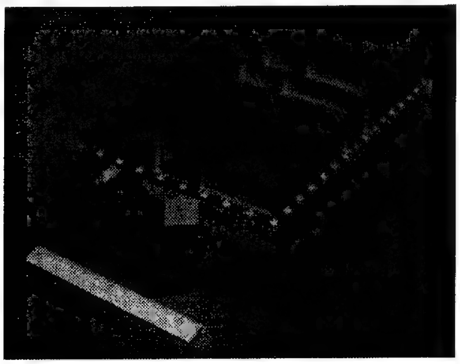


Figure 5. High Altitude Balloon Experiment (HABE)



TECHNICAL OBJECTIVES

- DEVELOP COMPACT, LIGHTWEIGHT, SPACE TRACEABLE, SOLID STATE, DIODE PUMPED LASER ILLUMINATOR
- PERFORMANCE GOALS
  - Diode Pumped
  - 500 mJ, 100 Hz @ 532 nm
  - 15 nsec Pulse Width
  - 5% Wall Plug Eff
  - < 1 cm Coherence Length
  - < 2 x DL Beam Quality
  - 0.05 m^3
  - 45 kg

MAJOR PARTICIPANTS

WRIGHT LABORATORY
FIBERTEK
HUGHES

TECHNICAL ACCOMPLISHMENTS/STATUS

- FIBERTEK LASER SELECTED FOR HABE
- RECONFIGURE TO SUPPORT HABE (FIBERTEK)
  - 60 Hz Operation Conversion
  - Longer Pump Pulse Modifications To Achieve ≥ 500 mJ @ 532 nm (300 mJ @ 2x D.L.)
- DELIVERY TO PHILLIPS LAB IN APRIL 1994

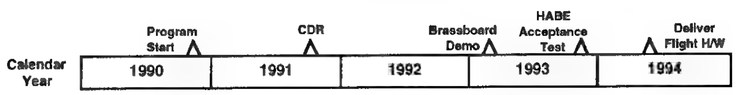
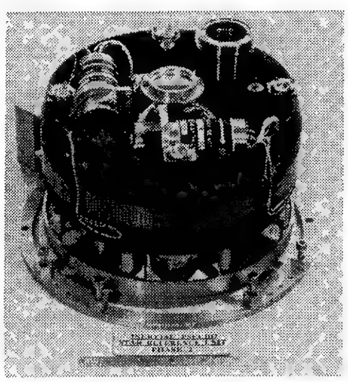


Figure 6. Illuminator Development



TECHNICAL OBJECTIVES

- PROVIDE ADVANCED PERFORMANCE STABLE REFERENCE FOR ATP-FC SYSTEM ALIGNMENT AND ANGULAR RATE MEASUREMENTS
- DEVELOP, TEST, DELIVER IPSRU UNIT FOR BALLOON AND/OR FUTURE SPACE ATP EXPERIMENTS
- REQUIREMENTS FOR HABE

- Reference Beam Jitter	≤ 100
- Angular Acceleration Limit	≤ 0.6
- Angular Rate Limit	≤ 2
- Drift Rate	≤ 0.06
- Isolation	–

MAJOR PARTICIPANTS

USAF Phillips Laboratory
DARPA
Charles Stark Draper Lab
Cambridge, MA

TECHNICAL ACCOMPLISHMENTS/STATUS

- COMPLETED ACCEPTANCE TESTING FOR HABE
- MEASURED 34 nrad OF REFERENCE BEAM JITTER (rms)
- DELIVERY OF FIRST UNIT APRIL 1994
- FABRICATION AND DELIVERY OF 2nd UNIT ON HOLD PENDING FUNDING

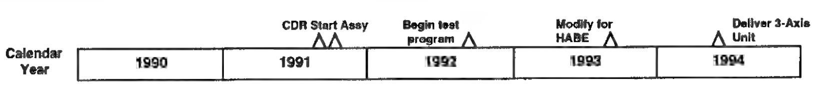
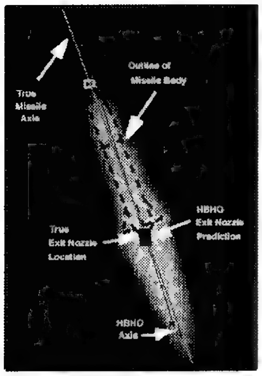


Figure 7. Inertial Reference Unit



MAJOR PARTICIPANTS

USAF Rome Laboratory
TASC, Reading, MA
Atlantic Research Corp.
United International Eng.

TECHNICAL OBJECTIVES

- DEVELOP AND EVALUATE KEY TECHNIQUES AND ALGORITHMS FOR ATTACK MANAGEMENT DECISION FUNCTIONS
  - Plume-to-Hardbody Handover
  - Aimpoint Selection
  - Target Identification
  - Target Damage or Kill Assessment
  - Target/Decoy Discrimination
  - Multiple-Target Scheduling
  - Autonomous Control
- DEMONSTRATE INTEGRATION OF DECISION FUNCTIONS WITH OTHER WEAPON SYSTEM FUNCTIONS IN HIGH FIDELITY COMPUTER SIMULATION
  - Show Feasibility Of Achieving Weapon Kill Rates

TECHNICAL ACCOMPLISHMENTS/STATUS

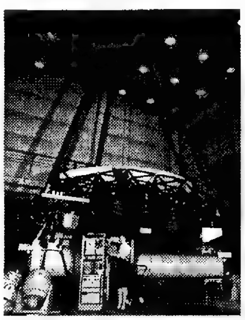
- STUDIES/ANALYSIS HAVE DEVELOPED AND TESTED BASIC ALGORITHMS
  - FC Algorithms Have Been Tested Successfully Against Measured Data (Starbird, Lance, Titan II)
  - Algorithms Delivered For Use On HABE
  - Passive Image Enhancements Explored To Improve Passive Fine Track Capability

HBHO Starbird data; Initial HBHO Algorithm; HBHO; Aimpoint; Target ID; Balloon experiment algorithms; Advanced Algorithm Development

Calendar Year	1991	1992	1993	1994	1995	1996	1997

Figure 8. Fire Control

SPICE OPTICAL STRUCTURE AT PHILLIPS LAB



MAJOR PARTICIPANTS

USAF Phillips Lab - Prog. Management
Lockheed - SPICE

TECHNICAL OBJECTIVES

- DEVELOP AND TEST ADVANCED COMPONENT TECHNOLOGIES FOR VIBRATION ISOLATION AND DAMPING IN LARGE SPACE STRUCTURES
  - Including Capability To Steer Structure Through Large (± 2 deg) Angles While Isolated
- DEVELOP AND DEMONSTRATE ACTIVE AND ADAPTIVE CONTROL TECHNOLOGIES FOR LARGE OPTICAL POINTING STRUCTURES
  - Goal of 100:1 Reduction In Base Motion Disturbance

TECHNICAL APPROACH/STATUS

- SPACE ACTIVE VIBRATION ISOLATION (SAVI) PROJECT COMPLETED 1990
  - 2 deg Steering, 50 dB Base Motion Isolation Demonstrated
  - Test Structure Became Core Of SPICE Project
- SPACE INTEGRATED CONTROLS EXPERIMENT (SPICE) DEVELOPMENT IN PROGRESS
  - Implemented HAC/LAC Structural Control And Demonstrated A Breakthrough In Mechanical Control: 28:1 Reduction In Unattenuated Farfield Line-of-Sight Error
  - System Tuning Has Led To A 65:1 Reduction
  - Plan To Include Passive Damping Treatments In FY94 To Achieve 100:1 Reduction

SPICE Start; SPICE Phase I; HAC/LAC Testing; HAC/LAC and Passive Damping

Calendar Year	1989	1990	1991	1992	1993	1994

Figure 9. Space Integrated Controls Experiment (SPICE)

6. APPLICATION OF ATP-FC ASSETS FOR TMD

The assets being developed for directed energy ATP can play a broader role in TMD assessments. The HABE balloon platform can accommodate a range of sensors and the existing package offers wide flexibility for testing TMD sensors and ATP or providing high resolution viewing of tests of TMD exercises or experiments. The platform sensors can collect data to address issues of weapon commit early in the target boost phase and the in-track flight guidance updates required for successful intercept. The supporting system engineering structure provides an existing means for developing certified data and data analysis products.

HABE can provide data to help address the common issues related to midcourse guidance updates and endgame hit-to-kill techniques.

Based on the previous discussion of issues for directed energy and kinetic energy systems, there appear to be common technology and technique issues in the sensor and guidance areas. Kinetic systems rely upon in-flight guidance updates similar to intermediate track needs for directed energy systems. The endgame and hit-to-kill for kinetic systems requires active signature with resolution and accuracy similar to directed energy systems.

In fact, there are two balloon payloads which could be available for testing related to TMD concepts. In addition to the HABE platform, Lawrence Livermore National Laboratory developed a balloon payload called Kestrel (shown on the right side of Figure 10) to be use primarily for phenomenology data collection with a range of passive and active sensors. The platform was designed for sea launch and recovery and includes a steering flat. The canister was successfully flight tested after a sea based launch. The sensors and canister development was stopped due to funding constraints and is currently in storage at Livermore.

The following ATP-FC assets have several potential applications for TMD testing.

The high resolution IR and visible sensors on the existing HABE or Kestrel payload can provide quantitative 3d imaging and tracking of TMD experiments or exercises. This data can essentially provide photo documentation for use in scoring and documenting tests.

Either payload can collect essential phenomenology data and associated elements can provide certified data to users.

The reconfigurable nature of the HABE payload make it useful for precursor field tests of TMD sensors or TMD integrated seeker payloads. HABE can provide data which is directly scalable to an operational system.

HABE can also provide direct data for either midcourse or endgame sensing and tracking data to address in flight guidance issue resolution for kinetic systems.

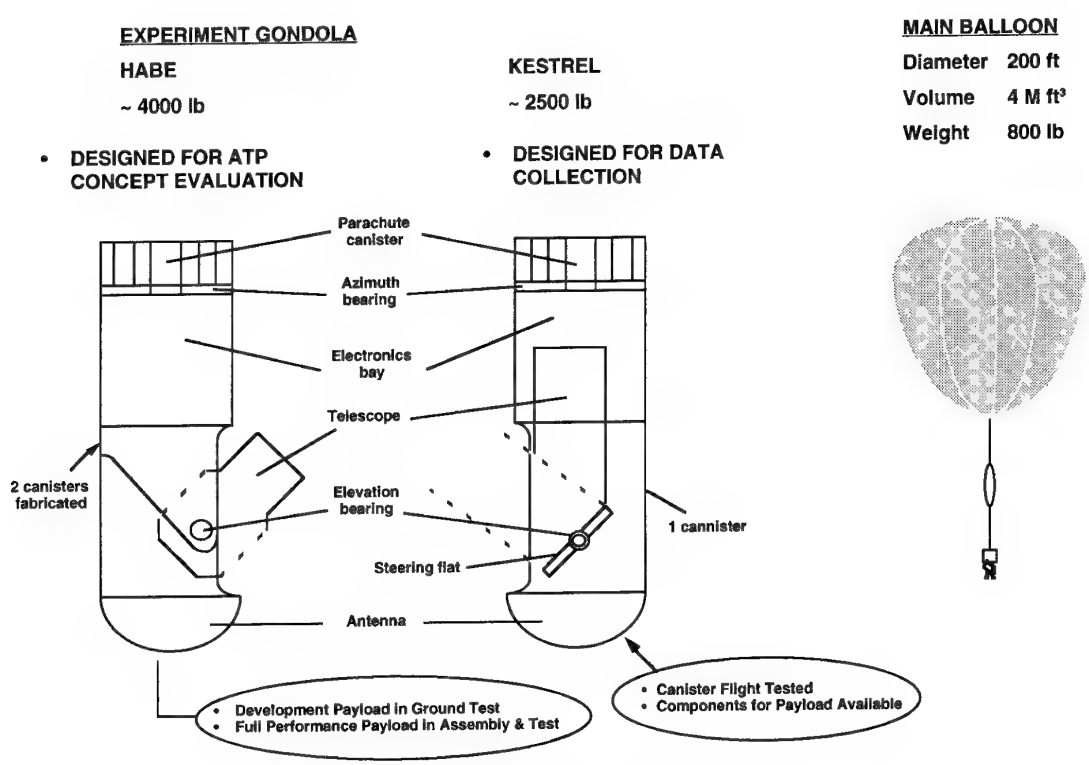


Figure 10. Experiment Platform Configuration

In addition, the extensive system engineering simulation support that exists in the ATP program can assist in experiment planning and prediction of experiment results. This allows numerous "what if" exercises to be run to increase the return from experiments or exercises.

Following are two examples of the applications just discussed.

Figure 11 illustrates potential sensor images available from the multi-spectral sensor package on HABE. The payload includes SWIR, MWIR and passive and active visible sensors and can produce images with resolutions from 100m down to 10cm. An LWIR design is available for HABE but is not in the current baseline.

These images indicate the quality of the data available from the baseline platform. Since HABE can be easily reconfigured, this level of sensor data can be collected with wavelengths of interest.

In addition to providing high resolution viewing of intercept tests, HABE can act as a full scale operational testbed. Figure 12 shows simulated images which could be obtained from sensors aboard an airborne surveillance platform like AWAC's viewing a post-burnout TMD hardbody. The images show high quality data which can be obtained from the testbed which can operate at the actual ranges of a target engagement.

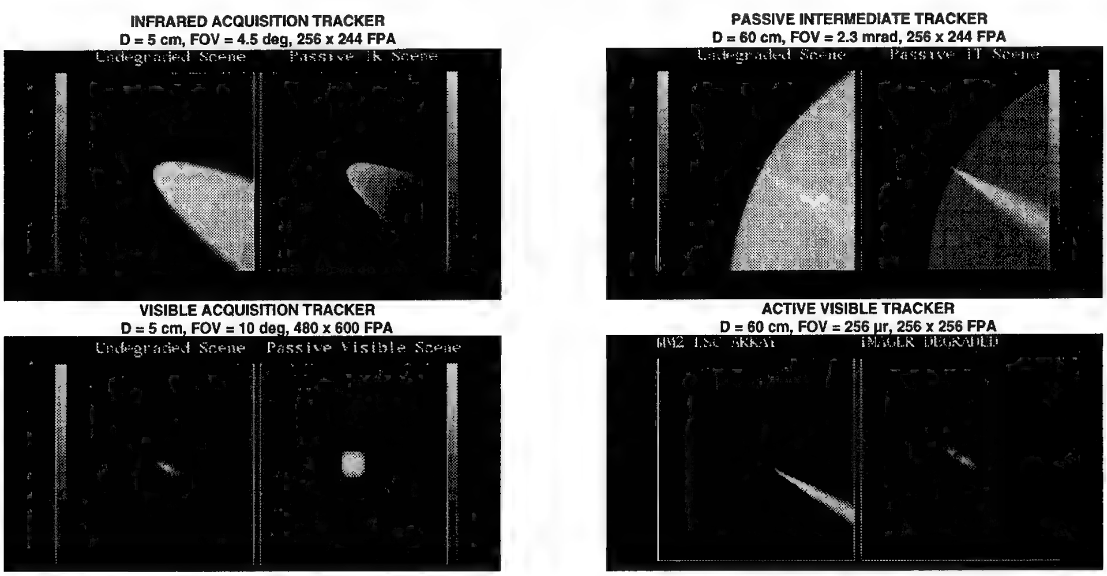
These examples show the potential utility of HABE and related assets for TMD tests. The cost benefit of using a platform like HABE depends on the specific implementation and need Figure 13 gives a notional view of the relative cost of obtaining high resolution data from different platforms. The airborne assets with small aperture systems are inherently low resolution and must stand off far enough from a test to insure human safety. Aircraft based systems with large optics can provide higher resolutions but they require expensive assets and ground support which drives up the cost. HABE operational costs are relatively low, the platform can station keep for hours and the current program can support 3-6 flights per year at current funding levels. The HABE platform has the potential to be both lower cost along with the advantage of a large optic and passive and active sensors which provide very high resolution.

7. SUMMARY

The benefits of the ATP assets to TMD are that the platform provides high resolution standoff sensors at low cost and can provide sub micro radian tracking and imaging of dynamic targets, active and passive multispectral data and non-cooperative fire control algorithms. The platform is relatively low cost and can be flow from 4-6 times a year for either sensor performance or phenomenology data collection. The process for collecting and certifying the data are in place and available today.

During the past decade we have made significant advances in ATP-FC technologies for ballistic missile defense. The current BMDO ATP assets in general and the HABE testbed in particular can be a key asset in developing TMD weapon systems by providing a means to collect key phenomenology data, test sensor and guidance components, or view and collect data to score test or exercises.

• **TARGET LAUNCHED FROM U.S. WESTERN TEST RANGE**



Time = 120 s **Range = 178 km**
Altitude = 153 km **Theta = 112°**

BALLOON PLATFORM PROVIDES MULTI-SPECTRAL SENSOR HIERARCHY WITH RESOLUTIONS OF 100s TO 1 MICRORADIAN (100 m → 10 cm)

Figure 11. Balloon Sensor Suite Imaging Examples

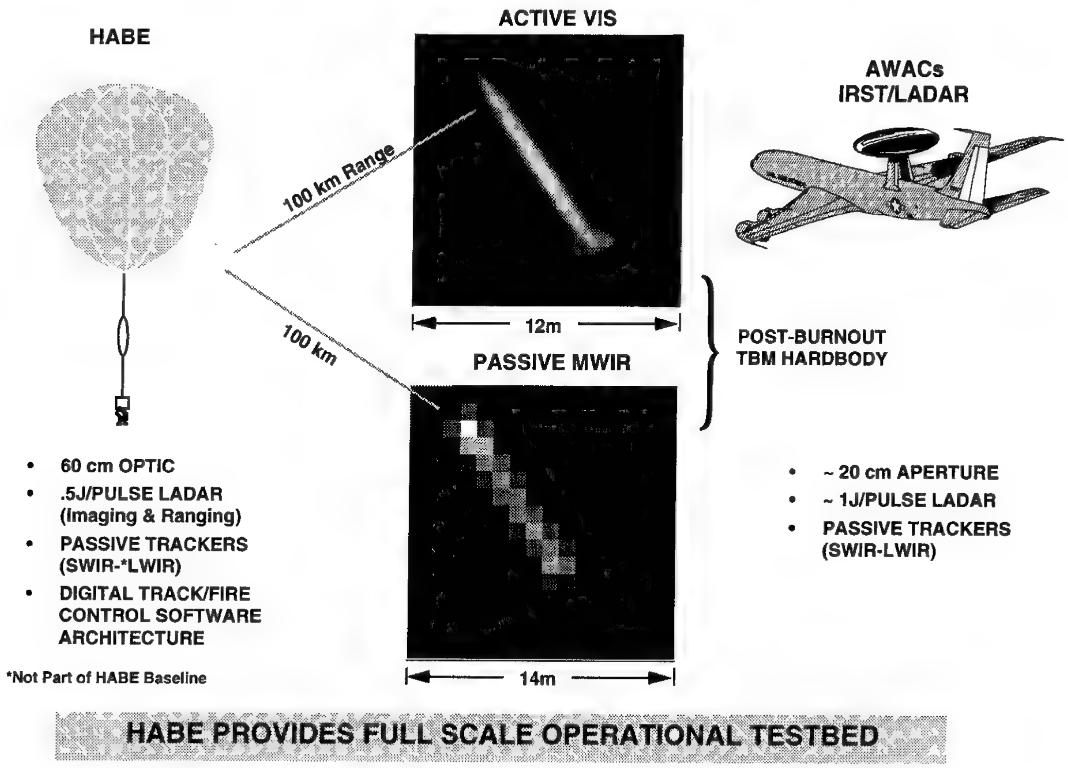


Figure 12. HABE Offers Potential Field Test Platform For Advanced Airborne TMD Sensors

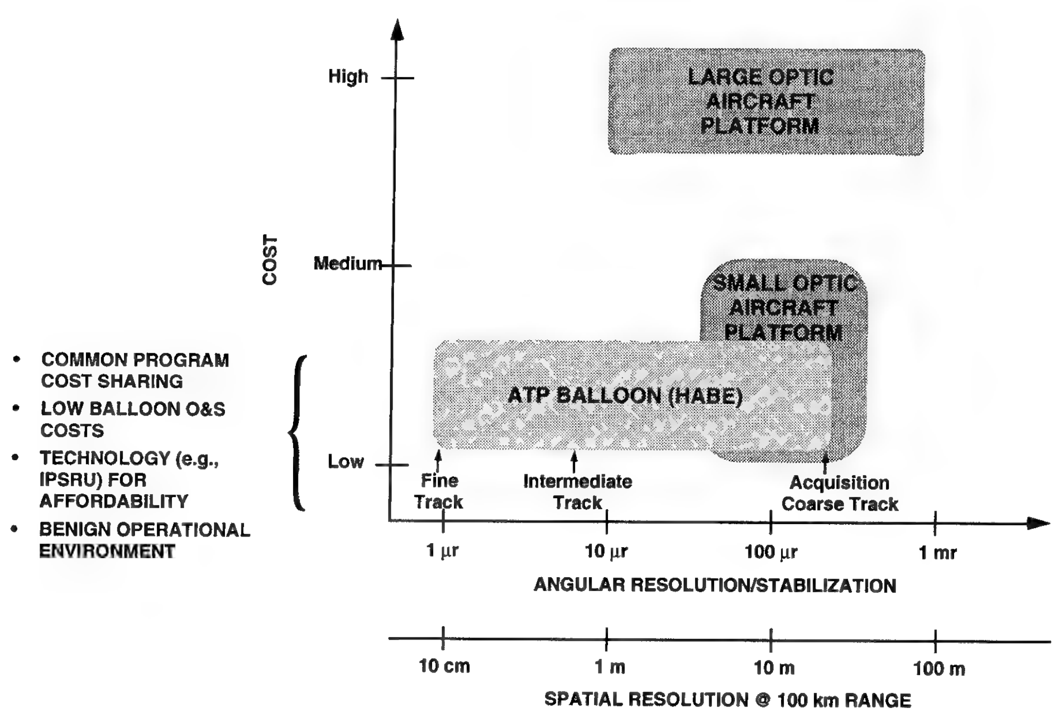


Figure 13. Quick Look Comparison of Balloon ATP and Existing TMD Test Assets

THE HIGH ALTITUDE BALLOON EXPERIMENT DEMONSTRATION OF ACQUISITION, TRACKING, AND POINTING TECHNOLOGIES (HABE-ATP)

D. Dimiduk, M. Caylor, D. Williamson, and L. Larson
Phillips Laboratory
Kirtland Air Force Base New Mexico, 87111-6008, USA

SUMMARY

The High Altitude Balloon Experiment demonstration of Acquisition, Tracking, and Pointing (HABE-ATP) is a system built around balloon-borne payload which is carried to a nominal 26-km altitude. The goal is laser tracking thrusting theater and strategic missiles, and then pointing a surrogate laser weapon beam, with performance levels and a timeline traceable to operational laser weapon system requirements. This goal leads to an experiment system design which combines hardware from many technology areas: an optical telescope and IR sensors; an advanced angular inertial reference; a flexible, multi-level of actuation digital control system; digital tracking processors which incorporate real-time image analysis and a pulsed, diode-pumped solid state tracking laser. The system components have been selected to meet the overall experiment goals of tracking unmodified boosters at 50- 200 km range.

The ATP system on HABE must stabilize and control a relative line of sight between the platform and the unmodified target booster to a 1 μrad accuracy. The angular pointing reference system supports both open loop and closed loop track modes; GPS provides absolute position reference. The control system which positions the line of sight for the ATP system must sequence through accepting a state vector handoff, closed-loop passive IR acquisition, passive IR intermediate fine track, active fine track, and then finally aimpoint determination and maintenance modes. Line of sight stabilization to fine accuracy levels is accomplished by actuating wide bandwidth fast steering mirrors (FSMs). These control loops off-load large-amplitude errors to the outer gimbal in order to remain within the limited angular throw of the FSMs..

The SWIR acquisition and MWIR intermediate fine track sensors (both PtSi focal planes) image the signature of the rocket plume. After Hard Body Handover (HBHO), active fine tracking is conducted with a visible focal plane viewing the laser-illuminated target rocket body. The track and fire control performance must be developed to the point that an aimpoint can be selected, maintained, and then track performance scored with a low-power "surrogate" weapon beam. Extensive instrumentation monitors not only the optical sensors and the video data, but all aspects of each of the experiment subsystems such as the control system, the experiment flight vehicle, and the tracker. Because the system is balloon-borne and recoverable, it is expected to fly many times during its development program.

INTRODUCTION

The USAF Phillips Laboratory in Albuquerque is developing and conducting a integration and technology demonstration experiment for the Ballistic Missile Defense Organization (BMDO) Directed Energy office. The purpose of the experiment is to integrate the Acquisition Tracking, and Pointing (ATP), and sensor technologies into a fire control system which is representative of that required for a Space-Based Laser (SBL) weapon for strategic and Theater Missile Defense (TMD). The experiment will demonstrate the functions required by the SBL through the point of hand-off to the weapon firing; thus technologies are chosen with attention to the utility in a space system. The program additionally supports the theater Airborne Laser (ABL) Directed Energy weapon system, demonstrating the fire control functions required up to the point of handover to the atmospheric compensation system. HABE-ATP advances a technology base which has applicability to LIDAR and other optical surveillance and fire control technologies for TMD.

Directed energy laser weapons are a subject of continuous study by the Department of defense for a variety of applications. TMD appears to benefit greatly from this technology, and efforts are being directed toward development of laser weapons for TMD. Either a Space Based Laser (SBL) or an Airborne Laser (ABL) appear to have substantial capability to destroy these ballistic missiles during the boost phase of flight. This capability stems from first principles of rocket design, which require staggering fuel-to-structural-mass ratios. this is manifested in minimal structural strength margins. The vehicle, while under powered flight, is under substantial stress due to internal pressure, as well as aerodynamic forces, and the force of acceleration. The majority of the rocket mass, of course, is highly flammable fuel and oxidizer. Destruction of the rocket during boost phase ensures that none of the fragments reach the target area, and they may in fact land on the territory of the attacker.

To engage the target from long range with a laser weapon during this vulnerable portion of flight is possible because of the development of high power weapon laser beams which have the desired lethality range. Weapon engagement, however, requires substantial advances in the integration of guidance, control, and pointing technologies. The short thrust duration of theater missiles (50-100 sec) requires very high performance tracking and pointing be achieved rapidly and flawlessly; thus the fire control designer is driven to a system which performs these preparatory phases of the engagement sequence as rapidly and autonomously as possible.

BMDO is now pursuing an integrated demonstration of these acquisition, tracking, and pointing technologies from a reusable balloon-borne platform. In addition to meeting the fire control needs of the laser weapon community, this experiment and the related technology development is demonstrating capabilities important to forward-based sensors which may be deployed to acquire state vectors for battle management of other boost, ascent, midcourse, or terminal phase defensive systems.

HABE EXPERIMENT OVERVIEW

The HABE mission goal is to very precisely track accelerating booster targets. (Figure 1.) Track must be with sufficient accuracy that stabilized rocket hardbody imagery can be obtained and processed in real time to compute a laser weapon aimpoint. The experiment will then propagate a surrogate weapon beam - a low powered laser beam - to the target for performance scoring. Motion of this scoring beam about the desired aimpoint on the target is an integrated measure of the limitations of the end-to-end tracking and pointing system.

The final objective of stabilizing the beam on the target to a fraction of a missile body diameter is to be achieved by demonstrating, step by step, the successively more difficult operational modes of the system. The experiment is being conducted at a nominal altitude of 26 km (85,000 ft) to achieve distortion-free imagery of the target, as can be expected by the SBL in space, or by the ABL after atmospheric compensation. Target engagement ranges of 50 - 200 km are sufficiently close to operational laser weapon system engagement ranges that accurate engineering performance scaling is possible.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

Thus laser weapon system designers can confidently specify ATP subsystems.

The ability to perform this tracking is not expected to be achieved in one step. The sensor/ control modes planned for this pointing and tracking systems are shown in Figure 2. The system sequentially progresses from processing target handoff information to a stable acquisition track; it then increases the track accuracy by stepping up the focal plane magnification and the control loop gain. It engages higher bandwidth fast steering mirror control loops, and ultimately the increases the track signal intensity by transmitting a visible laser illumination pulse, enabling active ranging and very high magnification active visible fine track. This last stage, while low in bandwidth because of the limited pulse rate of the illumination laser (60 Hz), is executed at very high control loop gain in order to permit making boresight adjustments to the marker (or surrogate weapon) laser which are much finer that the angular size of the target. These successive pointing and control modes must be stable and robust, and the autonomous transitions between them must be smooth and fast. While this general approach has been pursued for high energy laser Acquisition, Tracking, and Pointing/ Fire Control (ATP-FC) for more than 15 years, the technology tools available to carry out these functions have improved dramatically as the desired performance levels have gone up only modestly.

The challenge to achieving the tracking and pointing performance required by laser weapons is not so much dependent on any individual technology. The challenge is rather in integrating these individual technical capabilities into a combined system which can autonomously and robustly bring them into play as required. Specific developments have occurred which have resulted in markedly improved performance of each of the functions required for laser weapon pointing and tracking. These functions and the associated technologies are depicted in Figure 3. The value in this improved component technology is a substantial improvement in design margin for an integrated system. Because of the complexity of the integrated system, this design margin becomes an enabling capability on its own.

The HABE experiment, in particular, benefits from significant advances in SDIO/BMDO development of the Inertial Pseudo-Star Reference Unit (IPSRU), an advanced inertial reference; from the structural modeling tools and methodologies developed on the Space Integrated Control (structures) Experiment (SPICE) program; from the real-time image processing developed in the Advanced Modular Tracker (AMT), and from advanced diode-pumped solid state tracking illuminator lasers developed on the Solid State Laser Radar Source (SSLRS) program.

REQUIREMENTS AND DESIGN CONCEPT

The critical performance measures for a laser weapon tracking and pointing system are chosen to illustrate how well the laser beam weapon is stabilized on the desired target aimpoint. We define this performance for HABE based on three quantities: weapon (or marker) beam pointing bias, drift, and jitter. These are illustrated graphically in Figure 4. Bias is residual mean displacement of the beam from the desired aimpoint; drift is the low frequency (within the aimpoint maintenance control loop bandwidth) motion of the beam with respect to the aimpoint, and jitter is the pointing error at frequencies above the limited bandwidth of the system's very high gain active fine track control system. Most HABE quantitative engineering specifications were derived from pointing specifications in these three areas. For example, track sensors were designed to achieve the derived required noise equivalent angles and the optical magnification necessary for the desired control loop gains. Control loop bandwidths were chosen to provide sufficient margin in rejecting platform base motion so to meet the line-of-sight (LOS) jitter requirements. Processor suite throughput performance was sized by the bandwidth and accuracy requirements which flowed down from the control system design.

The required control system performance has been recently described in reference 1; the derivation and flowdown of the requirements are summarized here.

Because pointing errors can arise from many sources throughout the tracking and pointing system, the system design assigns an error budget to the subsystems. Design choices and component specifications were made in accordance with such a budget. The angular jitter budget for the balloon tracking and pointing system is also shown in Figure 4. The shaded boxes represent areas where subcomponent tests of actual or representative flight hardware has been incorporated into the budget. The nodes in the tree show root-sum-squared allocations/performance for each branch. As suggested earlier, technologies exist for each of the major functions to be performed to better than these budgets. The challenge in this experiment is to integrate the subsystems and to develop a sufficiently detailed understanding of the interaction between them. This understanding is embodied in validated modeling tools which the experiment develops. This understanding then enables the development of the autonomous fire control mode logic which will permit execution of these functions autonomously.

An optical pointing subsystem capable of the performance just described is quite complex. The design incorporates three wide bandwidth control elements along with the coarse pointing of the gimbaled telescope. Figure 5 depicts the major optical elements, control elements, and the feedback sensors used in the system. The main optical aperture is a 60 cm diameter telescope, used by the IR intermediate track sensor, the visible active fine track sensor, and for projection of the marker, or surrogate weapon, laser beam. The base motion-induced disturbances along these lines-of-sight (LOS) are sensed by an inertially stabilized platform which injects an alignment beam into the main aperture with an extended corner cube optical element. This alignment beam is sensed at a location physically near the visible and IR focal planes, and alignment errors are nulled by a fast steering mirror, thus stabilizing the LOS. The alignment beam also propagates to the separate optical bench for the illuminator and marker lasers. Separate fast steering mirror control loops use the inertial reference information from the locally-sensed position of the stabilized alignment beam, plus separate speed-of-light point-ahead and other correction information, to control the pointing of these laser beams. Coarse acquisition, ranging, and scoring sensors use optical apertures separate from the main 60 cm telescope; these functions do not require fine pointing or line of sight stabilization.

SYSTEM DEVELOPMENT

Simulation

The system concept illustrated in figure 5, which is considerably simpler than the actual pointing and tracking system, illustrates the complexities involved in achieving the desired system performance. To validate the engineering concept, the flow-down of specifications, and the adequacy of actual subcomponent performance, an end-to-end system simulation is used. Figure 6 is a diagram indicating the major modules in the simulation we have developed, HABESIM. Comparison of Figure 5 to Figure 6 shows that there is a clear correlation between each subsystems in the payload and simulation modules. The simulation is built from the SDIO-developed Attack Management Development Facility (AMDF) simulation tool. It is designed to model, in an integrated way, the performance of the entire system with any desired level of fidelity in the subsystem models. Because the program engineering methodology requires that each subsystem design iteration or component test result is incorporated into the simulation, incrementally increasing the simulation level of detail and fidelity, the simulation serves as the engineering accounting tool for the entire system. This simulation approach permits the end-to-end ramifications of any incremental design refinement to be fully understood. The simulation is periodically benchmarked with a full engagement run; the most recent benchmark examines a system engagement against a Black Brant Nine target rocket (which is representative of a solid-fueled TMD target) and is of high fidelity through passive intermediate track engagement phase, with some fidelity on the transition to active fine track.

Developmental Payload

Hardware development of a full flight system encompasses many elements: flight systems, ground systems; platform housekeeping, and full mechanical structure, in addition to the pointing system we are discussing. To partition this development, and to ensure flight

challenges are properly accounted for, a "pathfinder" developmental payload has been put together ahead of the full mission payload. This structure is being used to develop the coarse gimbals pointing system, its structure; the payload housekeeping and flight environmental control capabilities; the landing system; and the interfaces to the balloon systems. The developmental payload is used to develop operational capabilities and to provide field hardware experience for the laboratory team. It will demonstrate functionality of the system at altitude. Its visible-only optics system has full functionality up through the coarse point/ acquisition modes of the pointing system. It includes highly capable executive and data handling processors to execute and monitor all payload activities, including flight, mechanical, and pointing systems, with capability to log data at rates up to 20 kHz and at up to 16 bit accuracies. The payload environment (to include thermal and base motion) is also carefully instrumented.

The hardware for this payload's pointing system has been completely assembled. In Figure 7, it is shown hanging from a balloon-suspension compliance simulator. (Inertial pointing and attitude control has been initially demonstrated using this fixture.) For scale, the telescope which is facing the reader is 50 cm in diameter. The structure is about 4 meters tall, and weighs 5000 lbs. Two major features of the payload are to be noted from the photograph. The pressurizeable electronics compartment (without its pressure cover) is toward the top of the assembly. The gimbaled optical assembly is just below it; this assembly is sealed and pressurized for ascent and descent. The assembly rotates to a vertical position and then rubber seals inflate to seal the joint between the optics and the electronics compartments. The vehicle was designed for eventual use over water, with water landings, although all early flights are expected to be conducted over land.

To date, the all-visible-sensor tracking systems on this developmental payload have been exercised against stars to develop the inertial platform calibration algorithms. The system has also been used to acquisition-track small-scale solid-fuel rockets at 4.5 km range, producing angular rates and accelerations comparable to that expected for laser weapons systems engaging TMD targets. These small-scale rocket tests are to be an important part of the system development and test plan. Autonomous operation of the successively more-complex pointing system will be "wrung out" in this type of test. Results of the first system test with these rockets are being analyzed and used to increase the fidelity of the HABESIM simulation, and to prioritize additional development activities.

System Engineering Tools

The system modeling tools (described earlier) and a computerized engineering data management system (MISHABE) are used to facilitate transferring the test results from developmental activities to the incremental development of a fully-capable payload which meets the full mission specifications. The MISHABE system incorporates both a documents database and an analysis and data archiving capability which has all the functionality of the VISAGE system used on previous ATP experiments such as the Relay Mirror Experiment. It is being extended so some of the analysis functions are available in a menu-driven, graphical user interface so that engineers can perform analysis independent of the batch-mode processing needed for major system tests. The development of the analysis capabilities are based on the requirements described in reference 5.

PRIMARY PAYLOAD DEVELOPMENT

The primary payload to be used for the integrated pointing and tracking tests will be similar in external appearance to the developmental payload. However, considerably more complex and sophisticated sensor and pointing subsystems will be incorporated. In Figure 8, the hardware layout of the fully-gimbaled primary telescope is depicted, along with the associated components on the two optical benches. The optical sensors, interface optics, lasers, fast steering mirrors, and the inertial stabilization reference platform are all contained on the gimbaled structure. Not shown are the analog and digital electronics and the four processors which control these payload elements. These are located in the pressurized electronics compartment above this elevation-gimbaled assembly. Also not shown are the separate telescopes for the acquisition and ranging/ scoring sensors.

Sensors

The imaging sensors for the HABE mission include a combination of visible and IR focal plane sensors. Table 1 summarizes the performance characteristics of these target sensors on HABE. PtSi focal plane cameras, built by Hughes Aircraft, provide high dynamic range (12-bit digital) IR imagery in narrow wavebands which are custom selected for each engagement. The acquisition sensors use separate, 5 cm apertures, while the precision intermediate IR and active visible fine track sensors make use of the large 60 cm telescope. These high-magnification sensors are both near-diffraction limited. The IR cameras have been radiometrically calibrated; we expect an end-to-end system accuracy of ± 25 percent. The digital and analog focal plane cameras are being integrated with a digital tracking system and a digital data system.

It should be noted that SDIO/BMDO has conducted an extensive program to make accurate radiometric measurements of various targets to support a scientific phenomenology data base. The primary objective of HABE is to demonstrate pointing and tracking performance. However, because the tracking performance with a resolved target can be strongly affected by the observed phenomenology, it is necessary to conduct tracking investigations with nearly the same radiometric capability as in phenomenology investigations. Only with this information will it be possible to understand all the factors affecting tracking.

Table 1. HABE Sensors Suite

	ACQUISITION					
	IR	VISIBLE	INTERMEDIATE	ACTIVE	RANGER	SCORER
Wavelength (microns) (replaceable filters)	2.8 - 3.0 3.48 - 4.16	(0.4 - 0.7)	4.3 - 4.5 3.48 - 4.16	0.532 0.524	0.532 0.524	.860 .524
Aperture Diameter (cm)	5		60	60	20	20
Camera FOV (milliradians)	4.5°	> 100	2.3	0.256	1.0	.1
Pixel IFOV (milliradians)	300	> 200	9	1.09	--	--
Spot Size	2 pixels	~ 1 pixel	2 pixels (DL)	2-3 pixels	N/A	N/A
Focal Plane Size	256 x 244	480 x 600	256 x 244	256 x 256	Single Element	Single Element
Detector	PtSi	CCD	PtSi	CID	APD	APD
Pixel Pitch (microradians)	24	20	24	25	--	--
Number of Bits/Pixel	12	Analog	12	8	--	--
Frame Rate	30	30	60	60	--	--

Table 2. Control Loops Summary

Control Function	Purpose	Approach
Attitude Determination (Star Cal)	Inertial rate loop position initialization	Magnetometer, then star calibration
Open Loop Pointing (OLP)	Process external and pre-stored trajectory data for hand-off to coarse target acquisition (4° FOV camera)	GPS platform position. Kalman filter trajec estimation to command gimbal rate loop for LOS error less than 1/4 ACQ Camera FOV
Acquisition/ Track (ACQ)	Control Gimbal LOS to stabilize rates for hand-off to Passive Intermediate Track	Null-seeking loop using track inputs from w FOV IR camera to cage gimbal rate loop
Passive Intermediate Track (PIT)	Stabilized microradian track to provide imagery for plume to rocket hard body handover	Cascaded control of fast steering mirrors a gimbal LOS using magnified image trackin Point Inertially stabilized alignment beam at target; low bandwidth off-load to gimbals
Active Fine Track (AFT)	Track actively illuminated rocket hard body and compute aimpoint for surrogate weapon (marker) laser	PIT-loop architecture (above) with further magnified (10x) active-illumination visible sensor

Tracking Laser

The directed energy ATP community views active visible illumination as a requirement to reach the required track signal-to-noise performance. Visible illumination and sensing provides higher angular resolution than infrared. Recent advances have made suitable lasers available at 60 Hz repetition rate, allowing increased active track bandwidths. The HABE experiment is continuing the development of the SSLRS lasers developed for SDIO by two contractors. These Nd-based diode-pumped lasers are frequency doubled to obtain 0.5μ radiation. The lasers have been specifically integrating the laser into the flight platform, especially in developing a flight laser cooler for the payload system.

Laser-related issues to be explored in the active tracking program include "jitter coupling" which can occur when the laser far field intensity pattern is nonuniform, degrading the track; and laser speckle "noise" effects on the image to be processed by the tracker. These and other effects will continue to limit the range at which track performance can be achieved on low albedo (lambertian reflectivity) targets.

Control System

To accomplish the demanding autonomous acquisition and complex track functions derived from the mission requirements, a multitude of control modes are required. These modes drove the incorporation of the multiple control elements and feedback sensors described earlier in the conceptual design. This control system has been described recently in reference 1; an overview will be presented here. The control modes are summarized in Table 2. The modes are listed in the order that they are executed in a normal engagement. However, loss of track would require different mode sequences. To implement these modes in a flexible manner, a digital control architecture was selected, despite the demanding bandwidth requirements in the inertially referenced fast steering mirror loops (goal 500 Hz). The outer optics gimbal loop is a 10 Hz bandwidth rate loop with rate feed-forward, in order to follow the dynamics of an accelerating booster. The dynamics of the boosters in the TMD scenarios are the most stressing in the trade studies to date. The architecture of the nanoradian widebandwidth LOS stabilization system is somewhat unique compared to lower-performance tracking systems; its role in the implementation of the Passive Intermediate Track (PIT) mode will be described to illustrate the concepts. An overview of the digital processing implementation will follow this description.

LOS stabilization using the precision IPSRU beam is incorporated into both the PIT and the Active Fine Track (AFT) modes. The IPSRU concept is described in detail in reference 2. As described in Table 2, after the pointing system has stabilized an IR acquisition track of a target rocket plume, an intermediate track of with an IR sensor having 30 times more magnification is initiated. The sensor line of sight is stabilized by propagating an inertially stabilized laser beam from the IPSRU through the optical train. The alignment beam is injected into the primary of the 60-cm telescope by an extended corner cube. The displacement errors on the propagated beam are sensed by an Alignment Position Sensing Detector (APSD), driving an autoalignment fast steering mirror to null. Track errors sensed by the IR focal plane bias the IPSRU beam to maintain it pointing towards the target. The IPSRU errors are off-loaded at low bandwidth as steering commands to the main system gimbals, on which the telescope and the entire optical system are riding. The PIT mode will be handing off to an active track mode after plume to Hard Body Hand Over (HBHO) computations are performed to permit laser illumination of the hard body. Figure 9 shows the PIT mode from a controls viewpoint. The IPSRU alignment beam interacts with the illuminator control loop for the active tracking illuminator laser; a similar loop to controls the marking, or scoring laser, but is not shown. The control loop topology for this high bandwidth track differs substantially from the acquisition track loop which interacts only with the main gimbal rate loop. Further description of the parts of the system can be found in Ref. 1. Substantial attention is being devoted to the implementation of the digital control system mode switching. Transitions to the PIT mode from acquisition track, and from this mode to a similar-topology active fine track, must be smooth in order to acquire in the successively higher gain modes, and minimize the overall time required to achieve aimpoint selection/maintenance. A more detailed control simulation, in addition to HABESIM, is being used to understand the complex optical-controls interactions in these mode changes.

Error signals for these PIT and ACT loops are taken from both the image-tracking sensors (target track errors) and sensors which sample the inertially-stabilized alignment laser beam (platform dynamics/base motion errors). Optimizing specific parameters of the multiple control loops required here is one of the major objectives of experiment simulations and the experiment itself. The data from the extensive instrumentation of the control system, processed by the data handling processor, is a key component of the pointing experiments. The HABE controls team's previous experience on directed energy ATP system demonstrations, such as the Airborne Laser Laboratory and the Relay Mirror Experiment, suggest that real-world effects may lead to different optimization than one finds in laboratory integration.

HABE PROCESSOR SUITE

Because the chosen design implements most tracking, pointing, and control functions digitally, substantial real-time processing capability is required. Autonomous operation requirements and the need for a high bandwidth, flexible data acquisition system adds to processing load. The chosen architecture encompasses 4 processors: an executive which handles all communication with the ground and the balloon flight control system, and starts and supervises all computational processes; a fire control (tracking) processor which digests the imagery and other optical sensor data in real time; a Data Handling Processor (DHP); and a pointing Control Processor (PCP). The processors are networked with a "SCRAMNet," which uses 2 MByte memories in each processor which are "mirrored" between nodes with high speed fiber-optic links. The "mirroring" latency is 800 nsec or less. This processor system architecture is illustrated in Figure 10. The 4 VME-bus, M68040-based processors all run a commercial real-time derivative of the UNIX operating system, VxWorks. The Digital Signal co-Processors (DSPs) in the PCP run commercial proprietary kernels which are specifically designed to interface to this operating system. The image processing in the fire control processing will be described later.

The entire processor suite is installed in the developmental payload described earlier, and many of challenging computational tasks were demonstrated in prototype form in the scaled rocket tests. An interim report is being prepared on these tests to describe a performance baseline for the system at this developmental stage. No performance optimization of the control system has been attempted yet; the efforts to date have focused on system functionality. The system did demonstrate unoptimized functionality of the gimbal rate loop and a simple interface to an acquisition track loop. The software architecture appears to be robust and is meeting system needs.

Pointing Control Processor Summary

The main gimbal pointing control tasks just described, while challenging from a complexity point of view, do not drive the processing bandwidth requirements for the PCP. Analysis of real time processing timelines to support the three 500 Hz digital control loops (which impose far more computational burden) showed analog-to-digital (A/D) conversion by conventional techniques would be the processing bottleneck. Micro-controlled Remote Signal Conditioners (RSCs), capable of synchronous or non-synchronous sampling and A/D conversion at up to 40 kHz and up to 16 bit resolution, are being developed. These will support the 14 bit control system dynamic range requirement, and off-load the A/D conversion task from the pointing control and data handling processors. This wideband pointing control sub-system is currently being tested in prototype form with 12-bit A/D converters; initial results indicate good processor timing margins. The testing includes use of the i860 DSP coprocessors for the real-time control and compensation computations, addressing the largest challenge in the computational timeline. The higher-performance 16-bit converters (RSCs) are also in prototype form and will later be retrofitted into the control system.

Optical Tracking in HABE

The fire control/ track processor shown in figure 9 is a variant of the Phillips-lab developed AMT. This is an advance imaging tracker built around commercial real-time image-processing "engines" which sit on a commercial Datacube bus. This tracker has been used at several Phillips laboratory ground optical observatories, and variants are being developed for many types of optical image tracking besides the HABE mission. Further details on the design core can be found in reference 4.

The driving reason for incorporation of the modular, upgradeable image processing capability is that the varied and challenging tracking tasks required for autonomous laser weapon ATP. For example, each of the tracking cameras presents substantially different types of images because of the various wavelength bands being used for the various track modes. The characteristics of each video signal, in terms of frame rate, background, and noise need to be dealt with differently within the track processor. Also, the distribution of plume luminance is time-varying during a rocket's ascent, meaning the plume image centroid moves with respect to the rocket body. Because the intermediate fine track IR sensor will spatially resolve these plumes, this spatial distribution of energy can affect the track point, complicating the computation of a rocket hard-body location. This drives a requirement for relatively sophisticated image tracking techniques such as leading-edge track along the velocity vector, and/or correlation tracking. The experiment will be developing and testing further advances to this modular track control processor.

To facilitate this development, a Tracking Analysis Station (TAS) has been assembled. This is a ground version of the AMT tracking processor with an interfaced workstation; the combination has been optimized for analyzing digital or analog video data at real-time rates, either on- or off-line. It is being interfaced to the MISHABE data analysis system. The interface enables the integrated use of image processing analysis tools and linear signal analysis tools, so that, for example, control system data and video data from a test can be acquired, time-synchronized, and then both sets of data can be available for integrated analysis.

Flight Data Acquisition System

The effect of subsystem performance variations on combined system performance is a key issue to be studied by HABE. The digital instrumentation system controlled by the DHP has been designed to be highly flexible, so that as performance-limiting effects are uncovered, instrumentation can be improved along with the subsystem performance. The processor uses the advanced RSCs for some of the high-speed data acquisition, and since it is networked to the other processors via the SCRAMNet, it can have access to any of the variables being used by the other processors in experiment execution, at very high bandwidth. Reference 5 describes the baseline data acquisition plan.

The data from this experiment will provide important benchmarks as to what can be achieved in realistic operational scenarios.

Conclusions

We have described the status of a development program which will mature the various technologies needed for ATP into an integrated weapon subsystem. The key advances which enable the approach being taken are: The maturity of advanced networked computer processors and DSPs, their software design environments, and real-time operation systems; the development of light-weight, efficient diode-pumped solid state lasers; and the availability of an advanced angular inertial reference. Component and subsystem level understanding has matured to the point that a highly detailed engineering simulation is possible, and the simulation results lend confidence to the feasibility of the design approach. A partial-performance "pathfinder" payload system has been fully integrated from a pointing hardware point of view, and the first integrated system test has been completed with this article. Most components have been received and subsystem assembly and verification tests are underway for the full-performance integrated ATP system. The resulting pointing system capability will enable an important step forward in directed energy fire control, and will be a valuable testbed for achieving full weapon system prototype-level ATP performance. Two directed energy weapon systems, the Space Based Laser and the Airborne laser, view this demonstration as key to weapon system development.

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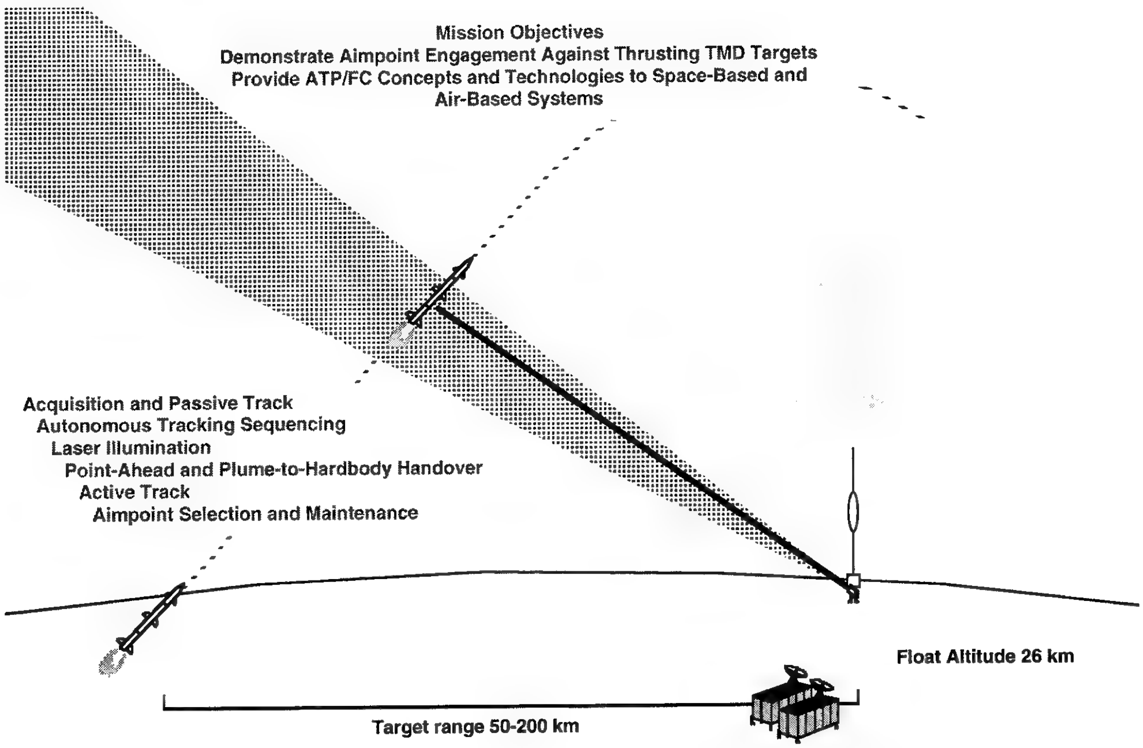
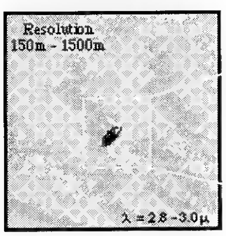


Figure 1. Overview of HABE-ATP experiment concept. HABE emulates space-based laser weapon pointing, tracking, and fire control by approaching the space disturbance environment (optical imaging disturbances and mechanical disturbances).

ACQUISITION FOCAL PLANE VIEW



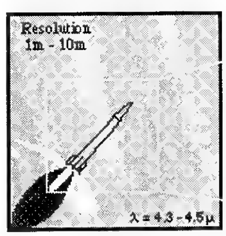
FUNCTION:

- Plume Acquisition

ELEMENTS:

- Handoff Data
- Slew
- Open Loop Point
- Gimbal/Structural Dynamics
- Closed Loop Tracking

INTERMEDIATE FOCAL PLANE VIEW



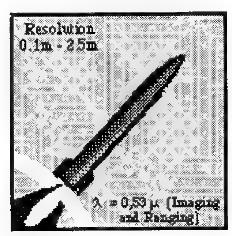
FUNCTION:

- Precise Plume Tracking
- HBHO

ELEMENTS:

- Wideband Inertial LOS Stabilization
- Track Robustness To Phenomenology

FINE TRACK FOCAL PLANE VIEW



FUNCTION:

- Ranging/Point Ahead Determination
- Hardbody Tracking
- Aimpoint Designation

ELEMENTS:

- Active Image Phenomenology
- Aimpoint Sensing

Figure 2. Directed Energy Weapon Fire Control Sequence.

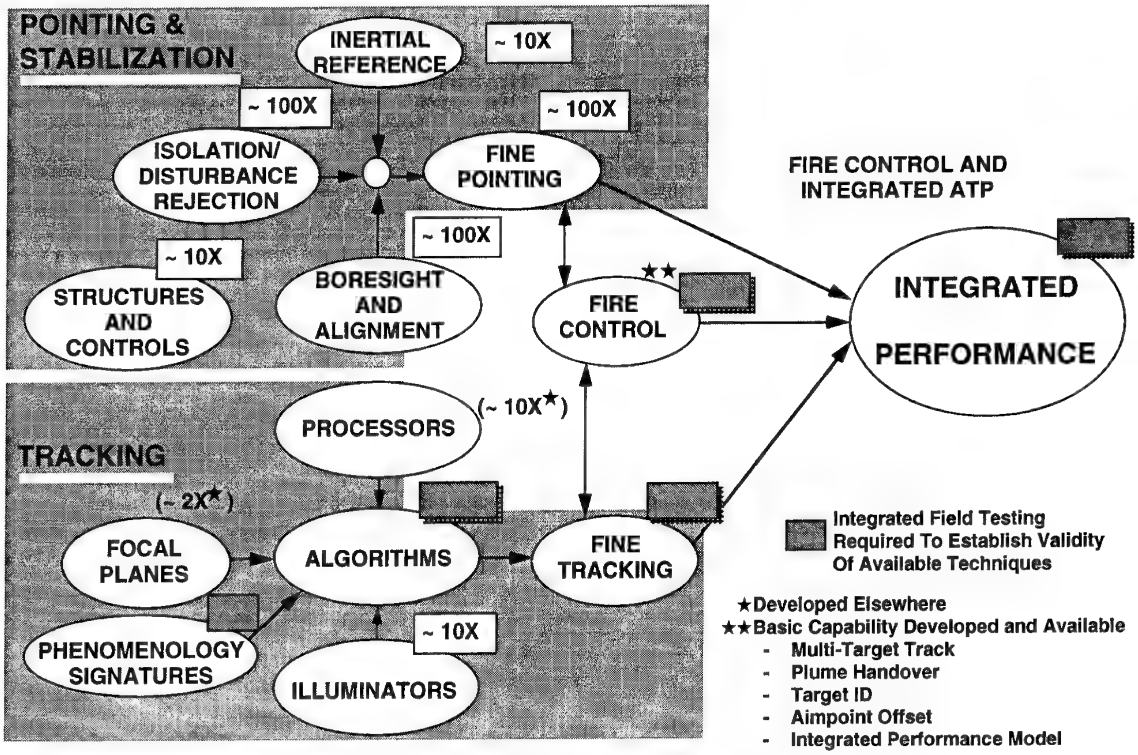


Figure 3. Dramatic advances in ATP-FC over the past decade.

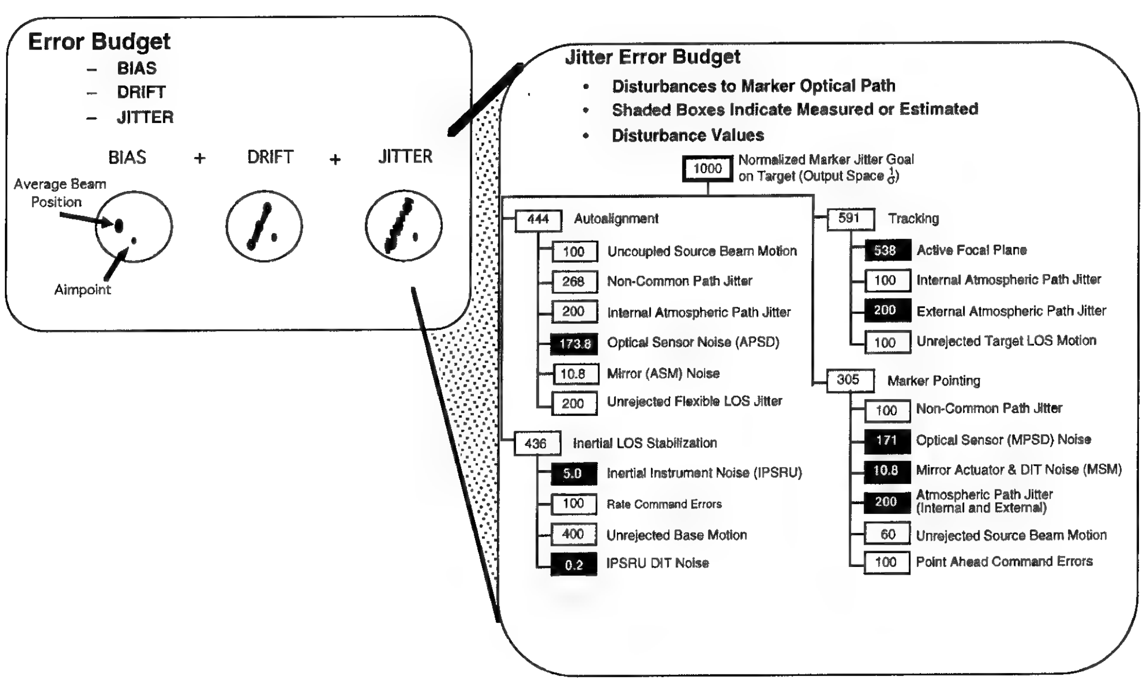


Figure 4. Definition of the measures of pointing performance, with an example of how performance requirements are flowed-down to subsystems in the case of jitter.

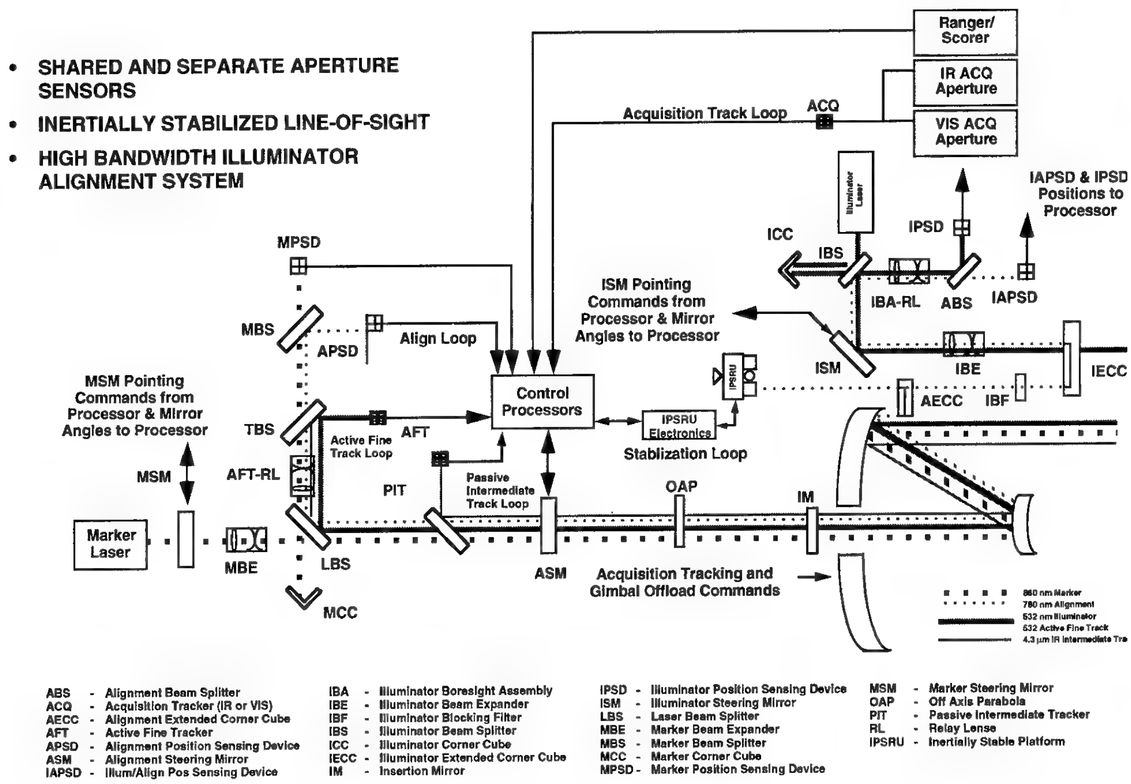


Figure 5. Payload functional concept. showng the controls/optical interactions.

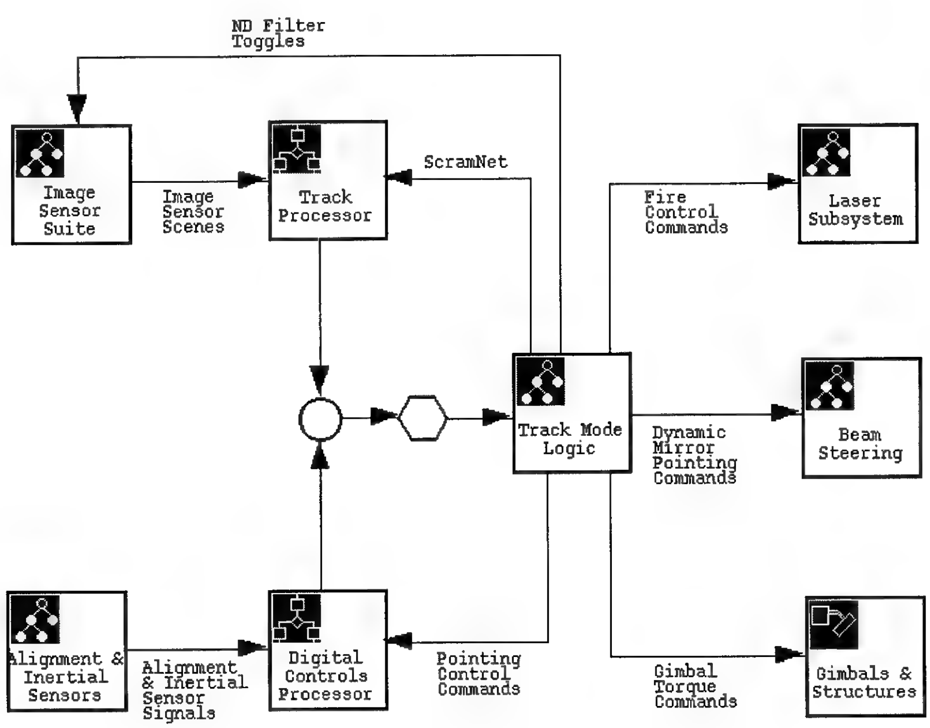


Figure 6. Payload simulation block diagram. Payload simulation is based on the SDIO-developed Attack Management Development Facility (AMDF) simulation tool.

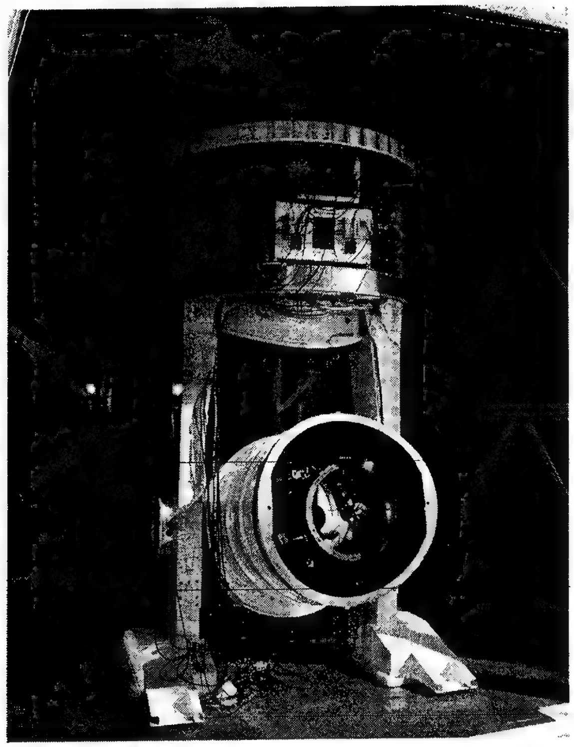


Figure 7. Photograph of the developmental payload in the testing laboratory. The payload is approximately 4 meters tall, and will weigh 5000 lbs. The telescope aperture is 50 cm diameter.

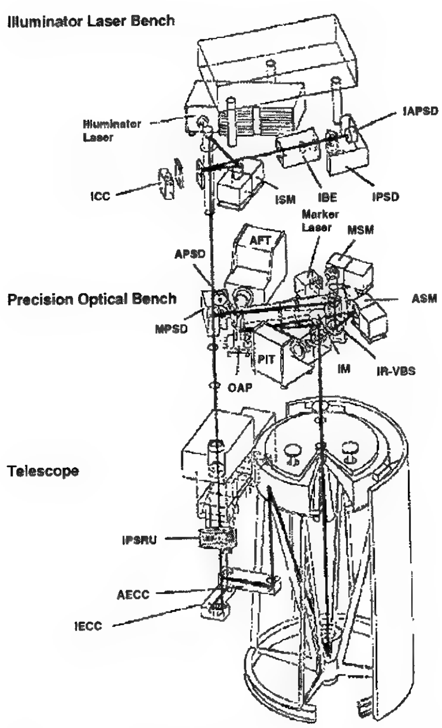
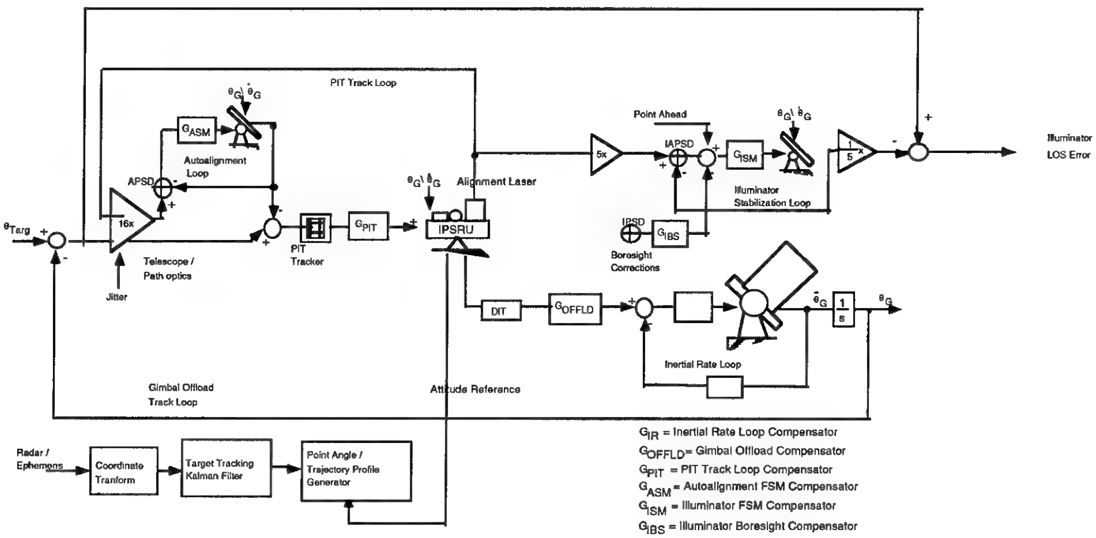


Figure 8. Payload optical layout for the primary payload.



Inertial LOS Stabilization

PIT Error Positions IPSRU Reference Beam

Illuminator Laser Fires

Design Criteria: LOS Error to 1/4 AFT Camera Field of View

Figure 9. Passive Intermediate Track (PIT) control mode.

- **THE HABE PROCESSOR SUITE IS DESIGNED TO REALIZE THE HABE ATP FUNCTIONS. THE PROCESSOR SUITE PROVIDES DISTRIBUTED INFORMATION PROCESSING FOR PERFORMING MULTIPLE TASKS IN REAL TIME.**

- **THE ATP FUNCTIONS ARE CONTAINED WITHIN THE EXECUTIVE, POINTING CONTROL AND TRACK/FIRE CONTROL PROCESSOR ARRAY.**

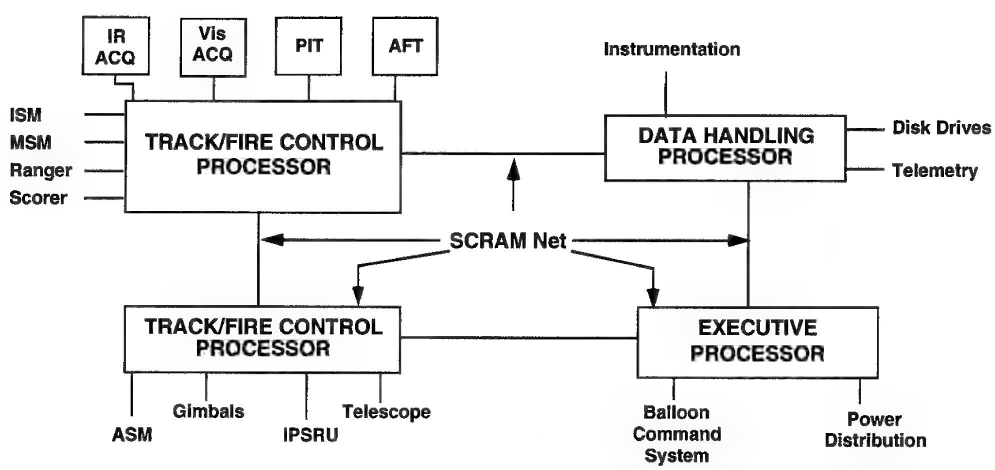


Figure 10. Computer subsystem top-level block diagram showing major features of the processor architecture. DSP co-processors and specialized micro-controllers are not shown, but play an important role in realizing the required processing bandwidth for many subsystems.

Integration Issues in Modular Mission Management Aid Development

F.M.Watkins, C.A.Noonan, K.Roberts
British Aerospace Defence Limited
Warton Aerodrome, Warton, Preston, Lancashire PR4 1AX, England

N.K.Upton
British Aerospace Defence Limited
Farnborough Aerospace Centre, Farnborough, Hampshire GU14 6YU, England

1. SUMMARY

The Mission Management Aid (MMA) programme at British Aerospace Defence includes research in the areas of Sensor Data Fusion, Sensor Management, Tactical Situation Assessment and Tactical Decision Aids. Each project has developed and continues to refine workstation prototypes. As the technology in these prototypes matures they are used to update and improve an integrated MMA system prototype.

This paper is concerned with the integration process and the issues surrounding it. The factors which influenced progress during integration include the use of compatible development platforms and programming languages for the prototypes, and the choice of a host architecture which allowed a flexible approach to the MMA architecture. The benefits gained from the integration framework include the ability to develop integrated displays and controls, to evaluate performance and effectiveness metrics, and to investigate the boundaries and interactions between the subsystems.

2. INTRODUCTION

To remain effective against the increasingly complex and diverse scenarios they will be expected to face, future tactical fighter aircraft will be more sophisticated and versatile than the current generation. At the same time, there is economic pressure to reduce the crew in number, in order to reduce aircraft weight and training and support costs. A smaller crew will be required to manage more numerous aircraft systems. The time taken to assimilate information, to decide on action and to carry it out will affect the lethality and survivability of the aircraft.

It has long been predicted that computerised Mission Management Aids will play a big part in shortening this information - decision - action cycle. To achieve this they will have to present information in an intuitive manner and have the confidence of the crew. They must be flexible and capable of reacting quickly to changing circumstances and new intelligence.

British Aerospace Defence has a comprehensive programme of MMA development for the Air Defence scenario. A series of workstation prototypes in the areas of Sensor Management, Sensor Data Fusion, Tactical Situation Assessment and Tactical Decision Aids are being developed, and as the technology in these prototypes matures they are consolidated within an integrated MMA framework.

This paper describes the individual Mission Management Aid elements and examines both the issues involved in the integration process and the benefits to be gained from integration. It considers the likely thrust of progress in related areas in the coming years, such as sensor technology, data communications networks and on-platform processing capabilities, and predicts the effect that this progress will have on MMA performance and effectiveness.

3. MMA PROGRAMME

Mission Management Aid research began at British Aerospace Defence over eight years ago. It was realised in the early days that the size and complexity of the problem were great. As a consequence, a generic model was sought which would identify the major contributing components in the MMA process and highlight the critical requirements for investigation and research. It would identify the natural module boundaries. The MMA model which was devised is shown in figure 1. It comprises Sensor Data Fusion, Sensor Management, Prioritisation and Tactical Planning. At this level of generality the model may represent many sensor based, automatic Mission Management systems. It is not specific to air superiority aircraft and their operations.

Programmes were initiated to investigate the components of the model in air superiority applications. Studies of sensors and sensor suites deployed by current and future aircraft yielded information regarding the composition and quality of information arriving at the Mission Management system. Programmes of modelling and prototype development for the subsystems would yield processing options and prototype algorithms.

To promote concurrent development, the individual programmes were made as independent as possible. Whilst the constraints of the Mission Management system model and its modularity were observed, and compatible computers and development environments were employed, the processes were allowed to develop to satisfy their own particular requirements and constraints. The objective was to produce prototypes for Sensor Data Fusion, Sensor Management, Tactical Situation Assessment and Tactical Decision Aids in their own individual development environments, and to integrate

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

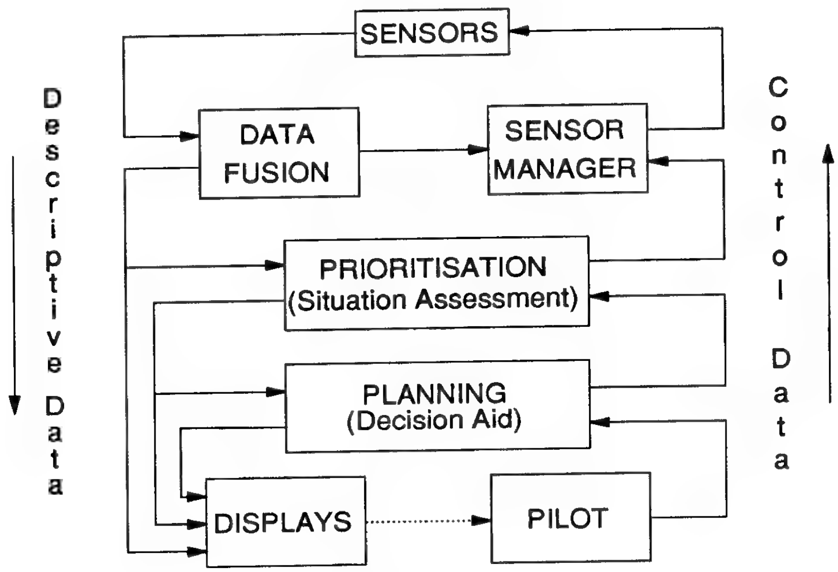


Fig 1: Mission Management System

them to demonstrate a complete and operational Mission Management system.

4. AIMS OF THE INTEGRATION

This section explains why it was important to perform the initial integration of the MMA modules relatively early in the overall programme.

4.1 MMA Architecture

The initial MMA studies defined a process model from which the component subsystems could be identified. This is not the same as an implementation architecture. By integrating early we were able to prototype the architecture in parallel with the modules, and hence reduce the risk involved in designing it from scratch. This helped us to maintain the modular aspects of the process model, allowing different versions of each module to be evaluated without affecting the rest of the system.

4.2 Process Model

We needed to confirm that the process model derived from the earlier analysis was appropriate to the MMA task. The boundaries between subsystems were investigated to ensure that there were no functional overlaps and, more importantly, no omissions. We needed to understand the input requirements of each module and to ensure that they could be and were being met and that their source was clearly identified.

4.3 Subsystem Interfaces

We wished to examine the interfaces between subsystems to confirm the *content* of the data exchanges, the *frequency* at which they occurred and their operational *context*. For the MMA system to operate effectively, the right data must be available and up to date at all times. Areas of conflict and incompatibility were highlighted in the course of the integration.

4.4 Data Quality

The quality of the data available is an issue for some modules, particularly those required to respond quickly to changes in the tactical situation. A lot of the workstation modelling for subsystem development relied on simple emulations of the expected data quality. The integration employed detailed sensor models in a realistic network, resulting in a better representation of the likely level of information available to the MMA.

4.5 Displays and Controls

Each subsystem has been developed with its own displays, some of which were for engineering and evaluation purposes and not intended for use by aircrew. We will use the integration rig to develop displays which will be refined towards a cockpit standard.

Similarly, the controls for each subsystem will be rationalized and a logical control configuration for the integrated system will be designed and implemented.

4.6 Performance and Effectiveness Evaluation

The integrated MMA must undergo evaluation. We need to produce evidence that the crew will be better able to accomplish a realistic mission when assisted by the MMA. Once integrated displays and controls have been developed, pilot assessments of the MMA will be carried out on an Air Combat Simulator. The first trials will assess the utility of the MMA as a whole, using a mixture of objective measures and aircrew opinion. The completed system will support comparative trials of alternative MMAs.

5. INTEGRATION FACILITIES

The integration process is taking place in two stages, using two types of facility. The first stage uses a flexible framework for architecture prototyping and display development, and then a more realistic system is used for formal assessments. The Systems Development Framework (SDF) provides the necessary flexibility for initial integration. The integrated system will then be transferred to the Air Combat Simulator (ACS) for aircrew evaluations. Both facilities make use of Silicon Graphics and SUN workstations, enabling direct transfer of C code from departmental workstations to the rigs.

5.1 Systems Development Framework

The SDF consists of a network of UNIX workstations, a cockpit mock-up with a projected display of the simulated outside world, and a software mechanism for fast reading/writing of model data from/to a central object orientated database. The SDF is illustrated in figure 2.

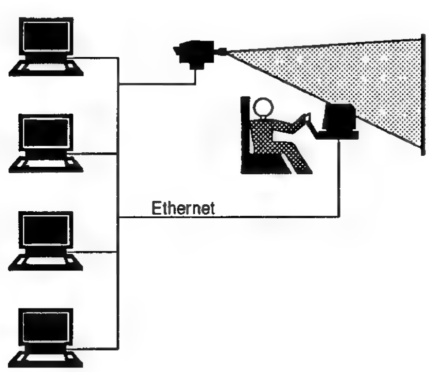


Fig 2: The Systems Development Framework

The MMA subsystems and simulation models are distributed among the workstations and run asynchronously. Communication between application workstations and the database workstation runs over ethernet. This system is not ideal for real-time applications, but the flexibility it offers in architecture definition outweighs any disadvantages at this stage.

5.2 Air Combat Simulator

The Warton Twin Dome Air Combat Simulator facilitates realistic and demanding 'Close In' and 'Beyond Visual Range' air combat. This may be between human pilots or human pilots and a combination of aggressive 'intelligent' computer controlled opponents in multi-player scenarios with pilots in secondary cockpits. A library of around 40 different types of aircraft are available for simulation and can be combined with any of the detailed missile and sensor models for assessment purposes. The aircraft cockpits within each dome contain three colour monitors on which a variety of avionic displays can be shown. Powerful distributed computing resources provide the flexibility and capability for the many different tasks which can be undertaken on the ACS. This system is illustrated in figure 3.

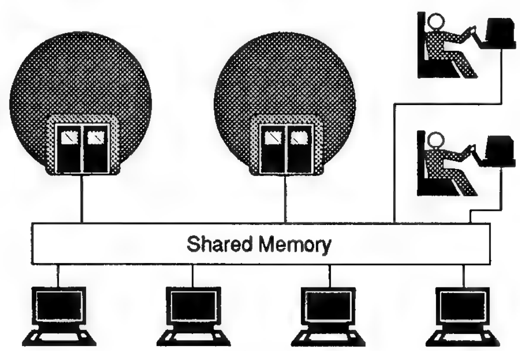


Fig 3 The Air Combat Simulator

This facility has already been used for pilot assessments of individual MMA subsystem prototypes, and will be used for trials of the whole MMA system.

6. MMA SUBSYSTEMS

The following sections describe the individual components of the MMA. They deal with the purpose and function of each subsystem, indicating the future direction of our research in these areas.

6.1 Sensor Data Fusion

A programme of development and evaluation of sensor data fusion for tactical aircraft operations began in 1989. One of the major objectives of the programme was to develop data fusion algorithms for use in an integrated MMA system. During the period up to 1992 suites of operational scenarios, sensor models, prototype data fusion algorithms and evaluation tools were developed. Collectively, they are referred to as the BAe Sensor Data Fusion Test Harness. The test harness and some of the results drawn from the evaluation programme were reported in [1].

Within the MMA model (fig 1), the purpose of sensor data fusion is to consolidate the situation data arriving at the aircraft via sensors and communication networks. The consolidated data is made available to the crew and aircraft subsystems as the prime source of tactical situation data. Other system models use the term Sensor Data Fusion differently, recognising different levels of data fusion. Within such a classification, ours is described as level 1 data fusion.

The model allows data to be received in the form of plots which may be regarded as single detections, as tracks which are based on a time series of plots and have a recorded history, and as images. Future air superiority aircraft will not routinely employ automatic fusion of all three types of data in a single stage process. A hierarchical approach is more likely, whereby image data will be processed to extract detections; these detections will be treated as plots and processed along with other plots to create tracks; and tracks from several sources will be processed together to update the tactical situation database.

The choice of performing fusion at image, plot or track level is often constrained by factors over which the fusion system designer has little influence. For instance, communicated data is often only available in track form and some sensors may be supplied in standard packages with built in plot extraction and tracking. Thus large parts of a fusion system architecture are likely to be defined by the needs and standards of the data sources. Where genuine opportunities for choice exist there are trade-offs which need to be observed. It is usually easier and more reliable to initiate new tracks on the basis of plots from a single sensor. However, once a track is established a more accurate estimate may be obtained using plots from multiple sensors. These trade-offs are dealt with in many books on data fusion (for example reference [2]).

Algorithms were evaluated on the test harness prior to incorporation in the sensor data fusion subsystem. The system model, shown in figure 4, was chosen to represent a typical sensor suite and associated sensor data fusion processing for a "state of the art" air superiority aircraft.

The sensor suite comprises RADAR, Infrared Search and Track (IRST), Electronic Support Measures (ESM) and data communications to friendly sensor platforms. ESM and data communications are fully implemented within the data fusion subsystem but have not yet been stimulated with on-line data during the MMA evaluations. The RADAR and IRST sensors each have their own in-built plot extraction and tracking.

Figure 4 shows a so called track-level data fusion process (alternatively referred to as "autonomous" or "sensor level tracking"). It implements the data fusion process in two stages. The first stage forms single source tracks and is distributed among the sensors and data communications terminal, each of which forms its own track list. Thus each data source employs a tracking algorithm which is optimised to its particular characteristics. The individual track lists are communicated to the data fusion process where the second stage takes place.

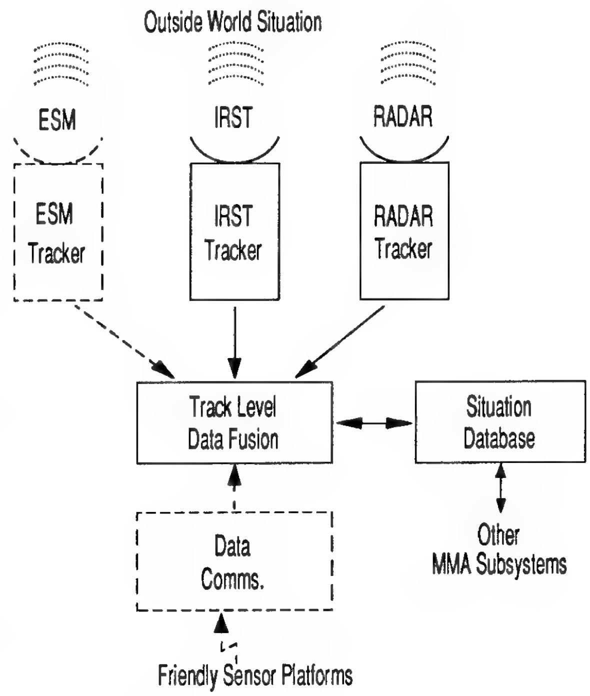


Fig 4: Sensor Data Fusion System Model

The track-level data fusion process fuses the tracks to create and maintain the situation database. The database is then the prime source of situation data for the aircraft and all its subsystems. It holds a single entry for each known target, comprising a consolidated, multi-sensor location

and motion estimate and a single, most likely, inferred identity. The following section describes the track-level data fusion algorithm in more detail.

6.1.1 The Data Fusion Algorithm

The data fusion algorithm is represented by figure 5. It accepts target data from the sensors and communications and updates the situation database accordingly. It comprises data alignment, gating, allocation, track management, state fusion and identity fusion. The functions of the individual processes are described below.

The algorithm employs batch processing of sensor tracks whereby the data received between time $t\text{-}\delta t$ and t is assimilated into the situation database within a single iteration of the data fusion algorithm. To enable this, *data alignment* extrapolates all data to the same point in time (t) and transforms it all to the same axis set.

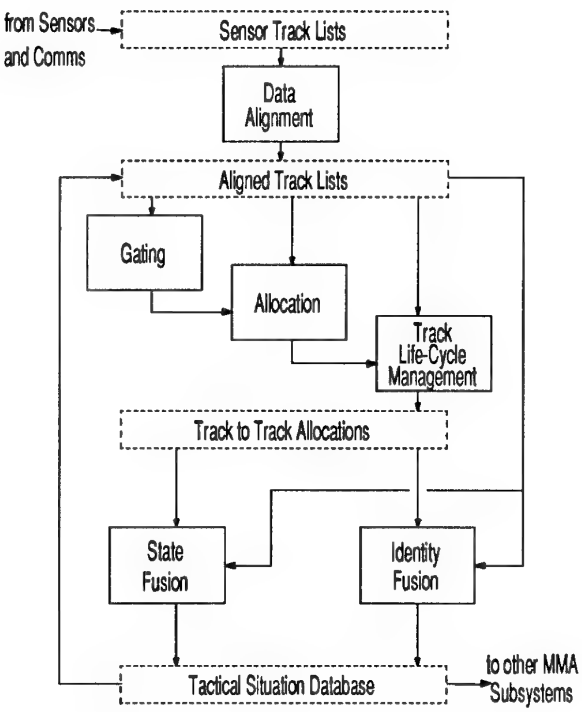


Fig 5: The Sensor Data Fusion Algorithm

The *gating* process applies a data reduction filter to the sensor tracks. By applying a series of statistical hypothesis tests to the possible sensor track combinations, it rejects all unlikely ones at an early stage.

The *allocation* process selects optimal sensor track combinations for data fusion. A likelihood is calculated for each feasible sensor track combination which represents the probability that the tracks arose from observations of the same target. By an optimal search process, it chooses the combinations which yield the greatest joint likelihood. This way, target tracks are established which offer the most likely explanation of the sensor and communications data.

Track life-cycle management is concerned with the "housekeeping" surrounding the maintenance of a track list. It creates new situation database entries when previously undetected targets are tracked for the first time; it ensures that existing entries are updated when new data becomes available; and it deletes tracks which are no longer within the potential coverage of any of the sensors or a cooperating friendly sensor platform.

State fusion and *identity fusion* consolidate the data for each situation database target observed by the multiple sensors to form the fused estimates. State fusion employs a rule based sensor hierarchy to form a composite state vector, comprising data from the "best" sensor contributing to each data element. Identity fusion employs a Bayesian algorithm to combine all the identity related attributes associated with each situation database entry, and produce a single inferred identity.

These algorithms were found, during the data fusion evaluation programme, to use processing resources efficiently and deliver suitably high estimation accuracy performance when coupled with a sensor suite similar to the one shown in figure 4.

6.1.2 Limitations on Sensor Data Fusion

The above data fusion subsystem has limitations when current sensors and data communications are used. These limitations will impair the performance of mission management systems if they remain unaddressed. They stem from the information quality provided by the data sources rather than from the data fusion architecture or algorithm. Alternative architectures and algorithms are prone to the same limitations.

First, ESM data is difficult to correlate with data from other sources because its line of sight estimation is so poor. This means that the likelihood calculations involving ESM are often ambiguous. The exceptions to this are situations where the opposing aircraft approach in well spread out formations. Otherwise, the result is uncertain identity estimation and MMA functions relying on identity are prone to poor performance. The obvious remedy is to improve the sight line estimation accuracy of ESM type sensors. A more radical approach might redefine completely the way identity is treated and used within such systems and avoid the ambiguities by asking slightly different questions of the identification process.

Second, communicated data from friendly platforms is highly under-utilised due to the restrictive nature of out-of-date communications standards and message formats. When this is addressed the data available to future generations of air superiority aircraft will be capable of full utilisation.

With these limitations lifted, a data fusion subsystem like the one described will provide accurate and reliable data to the Mission Management functions.

6.2 Sensor Manager

The Sensor Manager has three objectives. First, it aims to contribute to the provision of high quality situation data for the pilot by effective control of the tactical sensors. Second, the Sensor Manager will reduce pilot workload by automating much of the sensor control processes. Third, it will help enforce mission requirements such as covertness by ensuring adequate control of sensor emission levels.

These three objectives are achieved by translating *pilot nominated* and *autonomously generated* situation data requirements into precise instructions to the sensors. This translation must occur in real-time and it must exploit the different characteristics of the sensors.

The Sensor Manager will receive information from various sources, including the pilot, other MMA subsystems (primarily Sensor Data Fusion and Tactical Situation Assessment), and the sensors. The nature of this information will vary from data requirements and mission requirements to situation data. For example, the pilot may request data about a target (a data requirement), he may specify that the radar may not emit in a given sector (a mission requirement), and Sensor Data Fusion may inform the Sensor Manager of the position of a target (situation data).

The role of the Sensor Manager is to consider these different types of data, then, using this knowledge, make intelligent decisions about how the sensors should be utilised. That is, the Sensor Manager must devise a plan for each of the sensors.

The complexity of these plans will depend on the urgency of the current tactical situation as well as the sophistication of the Sensor Manager decision making process. If a particular target attribute must be quantified urgently then responsiveness must be paramount. Alternatively, if the situation is non-critical then the Sensor Manager may have time to produce plans that achieve optimal utilization of the sensors by applying them to satisfy a range of data requirements.

A Sensor Manager which uses a Knowledge Based Systems (KBS) approach has been developed and integrated with the other MMA subsystems on the SDF. It was developed as part of a knowledge elicitation exercise with military aircrew to determine the operational requirements of an automated sensor manager. A series of interviews were held with RAF pilots and navigators, using specially designed questionnaires. The first sessions investigated the broad aspects of sensor management for the various phases of air-to-air combat; later interviews went into more detail and included display issues.

The information gathered was analysed and encoded in KES (Knowledge Elicitation System) to produce a prototype Sensor Manager. This enabled engineers to gain a better understanding of the way in which the aircrew currently employ their sensors, as well as providing a tool for further knowledge elicitation.

This prototype emulates how aircrew currently control the sensors taking into account target proximity, the necessity for a periodic search to check for new targets, the need for improving data on targets currently being tracked, and the level of sensor loading. Initial concept prototypes in KES were easily transcribed to, and subsequently developed in, C.

A number of other data processing techniques are also being considered. The application of utility theory to multiple sensor management has been investigated. Linear programming methods [3] can be of value if the situation is non-critical and there is time to devise an optimal plan. A collaborative programme with the University of York is investigating the application of neural networks to the sensor management problem. It is likely that the production of a high quality Sensor Manager will require the synthesis of several data processing techniques.

The techniques just mentioned are very diverse, therefore it is essential that they have a common focal point to ensure that research adds value to the development of the MMA as a whole. A sensor management test harness exists to resolve any internal performance problems arising from the introduction of new system or processing concepts to the current Sensor Management model. Once these problems have been overcome, new prototype Sensor Managers will be integrated fully with the MMA system.

6.3 Tactical Situation Assessment

Situation Assessment was probably the least well defined of all the MMA subsystems in the original decomposition. It was seen in part as a means of reducing a highly complex scenario with a large number of target tracks into a smaller set that the Tactical Decision Aids could cope

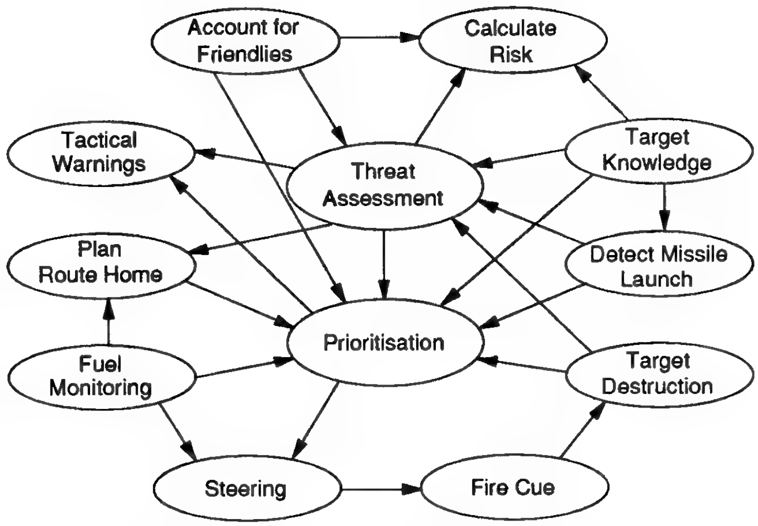


Fig 6: Tactical Situation Assessment Requirements

with. To this end a simple geometric filter, described by Mitchell [4], was developed. It is an enhanced version of this filter that has been incorporated into the initial integrated MMA.

It was nevertheless evident that there was much more to Situation Assessment than this, and so in 1992 the Tactical Situation Assessment project was started. Working closely with aircrew we identified several areas for research, which are depicted in figure 6 in the form of an influence diagram.

The complexity of the interactions between the requirements is clearly visible. Furthermore, no implemented system will have met its requirements unless the associated displays are lucid, intuitive and free of clutter.

Our analysis of the requirements led us to believe that Artificial Intelligence (AI) techniques could help us to unravel the complex requirements and their dependencies. We selected the KADS (KBS Analysis and Design Support) methodology [5] to follow in the development of this system. KADS is emerging as a European standard for the development of KBS systems. It consists of the following parallel phases:

Task analysis
This is a high level task analysis of both the current and proposed systems to identify tasks that will meet the top level requirement.

Cooperation Model
This is an analysis of the user - system interface to specify the information flow across it.

Expertise Model
This analysis is sub-divided into four tasks: *Domain Analysis*, where the knowledge in the domain is identified and structured in terms of its relationships; an *Inference Analysis* where the fundamental inference steps in each of the tasks identified by the Task analysis are defined and related to the domain knowledge; a further *Task Analysis* where a control structure is imposed on the fundamental inference steps; and finally a *Strategy Analysis*, where task execution schedule is defined.

Underlying all the KADS analysis phases is a comprehensive programme of knowledge elicitation giving the project a strong user (pilot) focus.

The Analysis Phase has produced a high level specification for the Situation Assessment MMA. We are extremely encouraged by the results to date. A systematic approach to such a broad and vague set of requirements has been invaluable. In fact we do not believe a solution would have been possible without the use of such a methodology. A conventional process decomposition would not have been suitable for this task. In conjunction with our Artificial Intelligence group we will produce metrics for the KBS software life-cycle that will aid in project management of future MMAs and other KBS

projects within BAe. On the development side we feel that the analysis has allowed us to select a more conventional language for the implementation (C++ in this case) due to the clarity of the specification provided by the KADS analysis. This will greatly reduce the risk in the integration exercise since C and C++ are the chosen development languages for the other MMA components. We believe the KADS approach can remove the need for prototyping with AI toolkits.

Our experiences of KADS are not all good. KADS is a general purpose methodology for Knowledge Based Systems and as such does not meet the special demands and constraints of real time software in the cockpit. Its most serious shortfall is the lack of any aid in defining a task strategy at the highest level. The control, scheduling, and behaviour of situation assessment tasks in real time is very important in this project. In other areas the methodology seems rather naive. For example, the cooperation analysis phase assumes that the user interface can be defined at the end of the analysis phase. This is totally unrealistic in an aircraft environment: useful displays can only be developed through a succession of iterative prototypes.

In summary, the use of an AI methodology has been invaluable in this project although KADS still has a way to go before it meets the complex requirements of cockpit systems. The use of KADS should greatly facilitate the integration of AI technology into our future products. We should begin to see a clear mapping from requirements, specification, design, through to implementation. We can at last begin to see a move towards validation and verification of KBS systems, though we are still some way from third-party implementation of in-house specifications.

6.4 Tactical Decision Aids

British Aerospace Defence is developing a number of prototype Tactical Decision Aids (TDAs). These include aids for both the air-to-air and the air-to-ground roles. For the air defence scenario we have prototypes of both the *advisory* type and the *informative* type.

COMTAC [4] and TACAID [6] are prototype *advisory* aids, similar in functionality but employing different technologies. In concept these aids are all-embracing - that is they recommend complete plans. Semple [7] tells us of the dangers inherent in advisory aids. The process by which the advice is derived must be as complete as the scope of the advice, before it can be of practical use in the cockpit. A partial solution in a wider domain is likely to increase workload, confuse the crew or even be ignored; this is not acceptable. Significant work remains to be done to make the COMTAC and TACAID plans comprehensive enough to be useful in the cockpit. These aids have not yet been included within the integrated MMA.

Informative TDAs do not create plans or make recommendations; they aim to provide the information required by the crew at the right time and in an easily assimilable form, but leave all the actual decision making to the crew. The necessity for completeness is thus eliminated; provided the pilot can understand the information and its limitations, he can make what use of it he will. The manner in which the information is provided is very important; the cognitive interpretation of the displays required by the pilot should be minimal.

TACMAP is one of the informative category of TDA. It provides a time-projected map of tactical information; this information usually comprises some kind of missile engagement zone, but the possibility of mapping other tactical parameters, either combined with the missile zones or in isolation, also exists. TACMAP is the TDA chosen for initial inclusion in the integration facility.

In its basic form, TACMAP shows "fire zones", where it is (or will be) possible to launch a missile at a target, and "risk zones", where there is (or will be) danger of being hit by an enemy missile. The algorithms to compute these zones use the situational data output from the Sensor Data Fusion system. Figure 7 shows an example of a TACMAP type display. Unfortunately a static monochrome picture does not have quite the same impact as a full colour dynamic display. Normally the fire zones would be green and the risk zones red.

The uncertain knowledge of the target state and future behaviour combined with the multiple options available to our own pilot can cause problems to a predictive system such as TACMAP. However, we have discovered that these effects can be minimised by combining different options onto a single display. The selection of suitable options to combine is not always straightforward, as the excessively large or exceptionally small zones that can result do not convey much useful information to the pilot.

This ability to combine options means that it is not necessary to represent each option rigorously, and so the modelling of physical and tactical parameters can be corrupted towards computational simplicity, thereby increasing update rates. Care must be taken in the simplification to ensure that any ambiguity from multiple options resolves smoothly according to the actions taken, and that the pilot is provided with adequate cueing as decision points approach.

The basic concepts of TACMAP have now been proven: the results of initial assessments on the ACS by BAe test pilots were very favourable; the computation can be

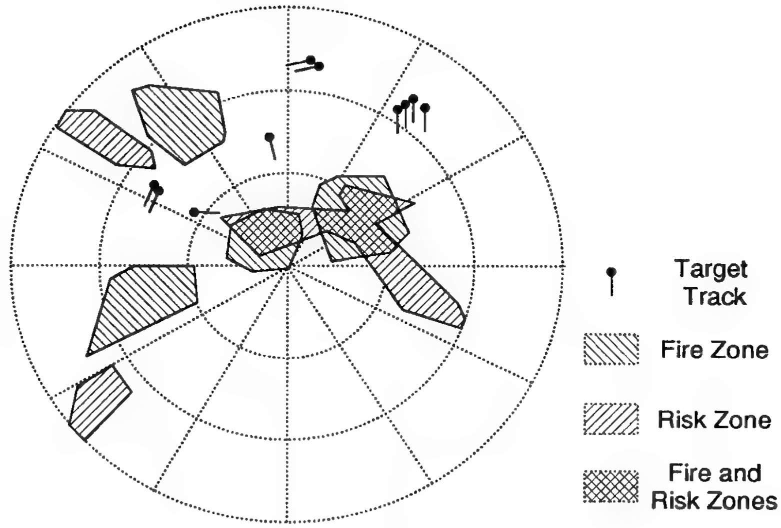


Fig 7: TACMAP Azimuth Display

performed sufficiently quickly for a respectable update rate (depending to some extent on scenario and parameters chosen); and the information can be displayed in a manner which the pilots can understand quickly and easily. Nevertheless much work remains to be done.

Relatively little research has yet been done on the discrimination of (adjacent) areas of colour, as opposed to discrete symbols. The effects of the cockpit environment, especially unfavourable lighting conditions, also need to be addressed. The number of colours (or shades of colour?) that can be discriminated will affect the number of distinct parameters that can be shown.

We know that many different parameters or combinations of parameters can be displayed in the TACMAP format. MMI studies have begun to determine which parameters are most useful, and in what combinations, distinct or aggregate. In addition we need to ascertain what level of control the pilot should have over these parameters.

More extensive tests need to be done to determine the effects of inaccuracies in the situation data used as input to the TACMAP algorithms. Initial studies with artificially noisy data have been encouraging; the integrated MMA offers the opportunity to carry out assessments with more realistic data quality and quantity.

These topics are all covered in our research programme which, now that the fundamental ideas are established, can concentrate on the issues surrounding the aircraft implementation of TACMAP.

7. THE INTEGRATED MMA

An integrated MMA system has been constructed on the SDF. It comprises Sensor Data Fusion, Sensor Manager, Situation Assessment and the TACMAP tactical aid.

7.1 The SDF Environment

The SDF has provided a flexible and convenient host for the integration exercise. Facilities such as the own ship platform model, the database management package, the mock cockpit, the scenarios and the communications were already established within the SDF. To complete the simulated environment, sensor models from the Sensor Manager test harness were installed. The MMA subsystem prototypes were then linked to this environment.

In addition, the usual facilities of the workstation environment were available to assist the developers during the initial setting to work of the system.

The result was an implementation in the form shown in figure 8. It has the major advantages that individual modules can be isolated from the rest and disabled, and any module can be easily replaced by an alternative version.

7.2 Scenarios

Simple scenarios with simple target behaviour were satisfactory for the initial studies. Subsequent refinement of the MMA will demand intelligent computer and/or human controlled targets, which are available on the ACS.

7.3 Architecture

The SDF operates an Object Orientated Database, with associated communications protocols, over a network of SUN and Silicon Graphics workstations. Applications communicate with the rig and with each other via this database. Each MMA module was implemented on the SDF as a separate application, writing to and reading from the database, as illustrated in figure 8. All data, descriptive as well as control, is sent into the database. No information passes directly from module to module.

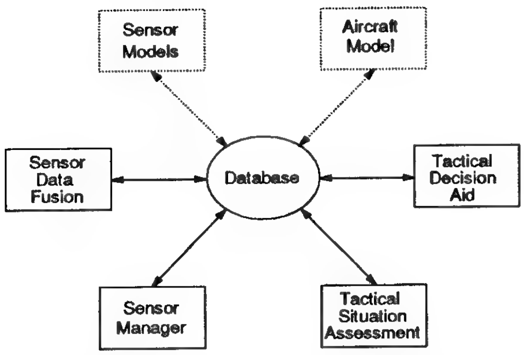


Fig 8: SDF Implemented Architecture

The great advantage of this arrangement is flexibility. It would be relatively easy to split or combine modules to create different process model forms. More complicated arrangements, whereby only a subset of the modules have access to the database, could also be accommodated.

7.4 Interfaces

The need for detailed interface definitions and communication standards became apparent at a very early stage. The data exchanges between the modules of an MMA are extremely complex and small changes in the interpretation of an interface definition were found to have the potential for profound effects on system operation and performance.

7.5 Timing Issues

In any system of this nature, there are potential timing problems in the interactions between modules. For example, the TACMAP display was slower to reflect changes and sometimes updated less frequently than the Sensor Data Fusion display. This is not entirely unexpected, because the TACMAP function is the last in line as well as being the most compute intensive.

The integration rig enables us to verify where delays are significant, and implement the most efficient solution to the architecture, the individual modules, the database, or a combination of these.

8. CURRENT STATUS

The integrated MMA system has been flown successfully against multiple, non-manoeuvering targets. Subsystems have been tested individually against manoeuvering targets. These targets are displayed on two touch screens; one showing the fused radar and IRST tracks, and the other showing the risk and fire zones generated by TACMAP.

The ease with which this initial integration was performed can be attributed to a number of factors. The individual subsystem boundaries emerged from the initial analysis and subsequent reintegration was a natural process; regular contact between teams was maintained throughout prototype development; a lot of care was taken in defining the interfaces between the MMA modules; the platform chosen to host the integration provides the necessary flexibility, and finally all modules were developed in a common programming language.

The next stage is to develop integrated displays and controls for the MMA, prior to transfer to the ACS for pilot assessments. The developing system will then be ready for flight trials in a fast jet.

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Conception de Systèmes de Surveillance et de Défense Anti–aérienne Multi–senseurs

C. Nahum et H. Cantalloube
Ingénieurs de Recherche
O.N.E.R.A.
BP 72, 92332 Châtillon
France

1. SOMMAIRE

Le logiciel ROSACE (Optimisation de Systèmes Réalistes, Aide à la Conception et à l'Évaluation), est développé dans le cadre de l'étude Méthodologie multi–senseurs en défense anti–aérienne, financée par la DRET (contrat n^{o} 91–34–846). Il s'agit d'un outil interactif, évolutif, portable, d'aide à la définition, à la qualification, et à l'optimisation de configurations de systèmes multi–senseurs pour la surveillance et la défense anti–aérienne.
Ce produit constitue un support pour l'expertise et la recherche de nouveaux traitements qui font intervenir la notion de *fusion d'informations* et qui sont susceptibles d'améliorer les performances du système. Ces algorithmes assurent essentiellement (mais non exclusivement) les tâches de *détection*, de *poursuite* ou de *classification* d'engins aériens et permettent d'analyser la fiabilité du système confronté à différents scénarii.

2. INTRODUCTION

La réalisation du logiciel ROSACE répond à deux objectifs principaux :
Il s'agit de développer un outil interactif, portable, d'aide à la définition, à l'analyse, à l'évaluation et à l'optimisation de systèmes multi–senseurs dans le cadre de la surveillance et de la défense anti–aérienne.
Le logiciel doit en outre offrir un support réaliste à des recherches théoriques sur les traitements, qui ont recours à la *fusion d'informations*, pour l'élaboration et l'expertise de nouvelles techniques de *détection*, de *poursuite* ou de *classification*. Ces algorithmes sont susceptibles d'améliorer les performances du système.

Afin de démontrer dans un premier temps la *faisabilité* d'un tel produit, certaines limitations sont imposées. Le système multi–senseurs est constitué de deux types de capteurs : des imageurs thermiques et des radars. Ces capteurs pourront assurer les tâches de veille ou de poursuite. Des simplifications ou des modélisations de certains phénomènes physiques seront adoptées. Dans le cas d'un système de défense anti–aérienne, des systèmes d'armes courte portée (obus anti–aériens par exemple) seront intégrés. De plus, un réseau de communications entre les différents composants sera spécifié.

La première version du logiciel ROSACE, est écrite en C (système d'exploitation Unix, environnement X–Windows). Elle comporte quatre modules qui argumentent cet article.
Le premier module, décrit dans le paragraphe 3, permet de définir un système de surveillance ou de défense multi–senseurs, par sélection et positionnement d'éléments (capteurs, postes de défense essentiellement) figurant dans une base de données. Une situation pourra être visualisée, puis éventuellement modifiée interactivement.
Le second module détaillé dans le paragraphe 4, propose une quantification des performances globales, optimales, du système et une visualisation des régions de *faiblesse*. Trois critères ont été retenus pour évaluer le système c'est–à–dire pour juger du positionnement et de l'orientation des capteurs et des systèmes d'armes sur un terrain. Il s'agit de sa *couverture*, (dont le sens sera précisé plus loin), de sa précision pour la *localisation* d'un aéronef, et du potentiel de *survie* d'un engin aérien situé dans la région couverte par le système. Ce dernier point pourra s'étendre par la suite à un calcul de *vulnérabilité* du système.
L'évaluation procure une bonne compréhension de la situation et suggère certaines modifications à apporter au système afin d'améliorer son efficacité.
Un système de surveillance ou de défense anti–aérienne, étant adopté, l'opérateur peut aussi le qualifier en le confrontant à différents scénarii. Un scénario sera essentiellement défini par les conditions atmosphériques, et les missions d'un ensemble d'aéronefs (missiles, avions, hélicoptères...) menaçants ou coopératifs. Le module de définition de scénarii comprend entre autres un éditeur de trajectoires, un synthétiseur d'images radars ou infrarouge...
Le module de simulations assure les trois tâches que doit remplir le système multi–capteurs : détection, pistage et classification (avec dénombrement) d'aéronefs. Une quatrième tâche de décision (attaque) devra être effectuée par un système de défense. Ces fonctions sont extrêmement dépendantes les unes des autres. Rappelons que l'objectif essentiel est d'évaluer la fiabilité, l'efficacité et la vulnérabilité du système multi–senseurs. Le quatrième module est donc une bibliothèque d'algorithmes de traitements. Le paragraphe 5 explique la façon d'orienter le choix vers telle ou telle méthode, selon la configuration et les moyens de communications internes au système.
Il est important de souligner ici, que le terme sytème ne

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

signifie pas uniquement ensemble d'éléments (capteurs, moyens de communications...) mais comprend aussi tous les traitements qui assurent les tâches requises. Ainsi le problème d'*optimisation* du système n'est pas restreint à sa configuration géométrique mais s'étend aussi au choix optimal des traitements. Illustrons ce point par le problème de la *détection* d'un aéronef. Plusieurs types de tests de détection multi–capteurs pourront être élaborés selon les moyens de communication internes au système. Il s'agira d'opter pour le test le plus performant (probabilité de détection maximale) qui ne requiert pas une complexité de calculs pouvant affecter le comportement du système.
Des statistiques sur la réussite d'une mission adverse, pourront être effectuées. Elles permettront de jauger les performances, la fiabilité, et les faiblesses du système.

Le logiciel ROSACE n'a nullement la prétention d'un Simulateur. L'objectif n'est pas de représenter dans leurs moindres détails tous les phénomènes physiques engendrés par une situation réelle. Il s'agit plutôt de dégrossir ses caractéristiques et de ne conserver que celles qui ont un véritable impact sur le comportement du système. Les résultats numériques attendus ne seront pas forcément des valeurs précises mais permettront néanmoins de qualifier le système.
Le logiciel ROSACE n'est pas un Système Expert dont la tâche serait d'orienter le choix des capteurs pour la conception d'un système de surveillance ou de défense. Par contre, il est tout à fait envisagé de coupler cet outil avec un système expert afin d'aider l'opérateur dans sa définition initiale.

3. DÉFINITION D'UNE SITUATION

Ce paragraphe présente le support du logiciel ROSACE, qui offre à un opérateur la possibilité de définir, de visualiser, et de modifier interactivement une situation de surveillance ou de défense anti–aérienne. Le paragraphe 3.1 précise le terme *situation*. La gestion informatique des éléments de la base de données est expliquée au 3.2, démontrant ainsi la souplesse du logiciel et son potentiel d'évolution selon les besoins, les informations disponibles, et la précision requise. Le paragraphe 3.3 présente une discussion dont le but est d'orienter l'opérateur dans son choix initial de capteurs (ceci pourrait être le résultat d'une analyse réalisée par un système expert).

3.1 Composantes d'une situation opérationnelle

L'opérateur spécifie une situation en sélectionnant, au moyen d'un menu, une zone géographique (zone de surveillance) dont la superficie est de l'ordre de la centaine de km^2. Cette zone est maritime ou terrestre selon le contexte. Une image numérisée du terrain peut être fournie au logiciel. La connaissance de l'altimétrie est d'une importance cruciale pour l'analyse de la situation : la portée des capteurs en dépend directement et les manoeuvres des assaillants s'y adaptent pour profiter des parties "aveugles". La végétation constitue aussi un facteur non négligeable, de par les effets de masquage et de "clutter" qui affectent les performances des senseurs. La carte de la zone est visualisée à l'écran afin d'aider l'opérateur dans ses démarches pour la définition du système.
L'opérateur dispose sur le terrain un ensemble de capteurs. Il précise donc leur position et leur orientation (axe de rotation de l'antenne d'un radar de surveillance, axe de rotation de l'axe optique d'un imageur thermique de veille...). Les senseurs pourront être co–localisés (par exemple dans un contexte naval, certains se trouveront sur un même bâtiment) ou délocalisés. La constellation de capteurs ainsi définie peut être mémorisée et restituée sur demande.
Des postes de défense (base sol–air, obus anti–aériens, missile auto–guidé ou télé–guidé) figureront sur le terrain.
Des points sensibles dont la protection doit être particulièrement assurée, sont indiqués. Ces points peuvent être des cibles pour l'assaillant, et représentent par exemple des bâtiments, des ponts, des postes de défense, ou encore des capteurs. Il est envisageable de considérer des parcelles, ou encore des objets en mouvement, tel un bataillon de chars.
Un réseau de communications entre les différents organes du système (notament entre les senseurs, les postes de défense et des unités centrales), est indispensable pour gérer la situation. Le débit des lignes de transmission, les délais moyens d'accès, le mode (mono ou bi–directionnel) devront être précisés. Ainsi, les différents processeurs de fusion répartis sur le réseau pourront connaître le type d'informations susceptibles d'être échangées ou associées (images, ensemble de valeurs numériques...), et par la–même opter pour une catégorie d'algorithmes de traitement. Ce réseau est représenté par un graphe. Trois grandes classes de débit sont considérés :

Haut débit (Ethernet 10 Méga–octets/s, fibres optiques 30 Méga–octets/s) : Transmission de quelques séquences vidéo (25 images/s) ou du signal radar non détecté (simplement démodulé).

Moyen débit (RS232 50 Kilo–octets/s) : Imagette au voisinage d'une menace potentielle, carte radar (Energie en distance–azimut) en temps réel.

Faible débit (Liaison sécurisée 500 octets/s) : Position, variance, confiance de quelques plots.

Ce réseau peut aussi comprendre des bus de communication, lignes de communication partagées entre plus de deux postes.

La spécification des *conditions atmosphériques* et des *missions*, fait partie de la définition du scénario auquel pourra être confronté le système. Il en est de même pour les *leurres* optiques (fumigènes, pots pyrotechniques) ou électro–magnétiques (brouilleurs).

3.2 Gestion informatique

Afin de rendre le programme évolutif et de lui conférer une ergonomie et une interactivité attrayantes, il a été

nécessaire de choisir une représentation maniable des différents éléments.

Une base de données est construite selon les informations disponibles et nécessaires à l'analyse du système et aux simulations de scénarii. Pour valider le logiciel, des données réalistes mais non classifiées (publiées dans le catalogue *Jane's Weapons & Systems*) ont été utilisées. Il est néanmoins très facile de les remplacer par les valeurs exactes du système opérationnel à tester.

Trois classes d'objets type figurent dans la base de données :

Classe 1	SENSEUR
Classe 2	ARME DE DÉFENSE
Classe 3	AÉRONEF

Chaque objet type est représenté en machine par une structure contenant le nom de l'objet, ainsi que ses caractéristiques. Le nom est aussi celui attribué au fichier qui contient les caractéristiques.

STRUCTURE objet type
↓
nom caractéristiques

Par exemple dans la classe 3, on peut considérer l'objet type AVION_1. Le fichier dont le nom est AVION_1, contient le modèle :

AVION_1 →

Paramètre	ex
SER	$5m^2$
Température	300°
Longueur	100m
Largeur	40m
Section	20m
Facteur de charge maximal	3g
Altitude moyenne de vol	4500m
Vitesse moyenne	300m/s

Remarquons que ces différents attributs seront utilisés pour l'identification de l'engin lorsque celui-ci aura été détecté par les senseurs, pour la simulation d'une mission, ou encore pour l'évaluation de sa vulnérabilité.

Dans le cas d'un radar de surveillance 2D, à impulsions, le type de paramètres retenus pourra être (Voir [1]) :

RADAR_3 ↓

Paramètre	ex
Longueur d'onde	0,05m
Puissance émise	100.10^3 W
Fréquence de Répétition	1500 Hz
Largeur d'impulsion	$0,5.10^{-6}$ s
Forme antenne	rectangle
Diamètre ou Long/Larg	$1,2x0,8$ m^2
Figure de bruit	4
Température de bruit	300 K
Bande de fréquence bruit	2.10^6 Hz
Couverture azimutale	180°
Couverture en déclinaison	40°
Durée de passage	10 s

Pour un radar de poursuite doppler, il faudrait préciser d'autres paramètres tels la forme d'onde (chirp, dents de scies etc...) et la variation de fréquence du signal en fonction du temps.

Ces caractéristiques sont nécessaires pour l'application de l'équation du radar qui fournit une *approximation* correcte, parfois suffisante des rapports signal-à-bruit, pour la synthèse des signaux radars, pour l'estimation des erreurs de mesure...

Les objets type de la classe ARME DE DÉFENSE, contiennent des caractéristiques de dispersion aérodynamique pour les obus anti-aériens ou de distance d'accrochage pour les missiles auto-guidés.

On définit ensuite des objets qui sont des objets type que l'opérateur positionne dans le temps et dans l'espace. On distingue trois classes d'objets :

Classe 1	POSTE SENSEUR
Classe 2	POSTE DÉFENSE
Classe 3	AÉRONEF EN VOL

Par exemple, un objet POSTE SENSEUR est par conséquent :

POSTE SENSEUR
↓
SENSEUR position orientation

On précise non seulement les coordonnées x,y et z dans le repère cartésien par rapport à une origine choisie sur la zone géographique considérée, mais aussi l'orientation dans l'espace de l'axe de rotation de l'antenne d'un radar, ou la direction de l'axe optique d'un imageur.

Un méta-objet est un ensemble (ordonné) d'objets issus d'une même classe. On a aussi trois classes de méta-objets :

Classe 1	CONSTELLATION DE SENSEURS
Classe 2	MOYEN DE DÉFENSE
Classe 3	MISSION

Le méta-objet CONSTELLATION DE SENSEURS est donc un fichier qui contient un nombre N d'objets POSTE SENSEUR ; eux-mêmes sont la concaténation d'objets SENSEUR (référés par leur nom), et de coordonnées spatiales.

La Figure 1 récapitule l'organisation informatique des données, qui a été adoptée.

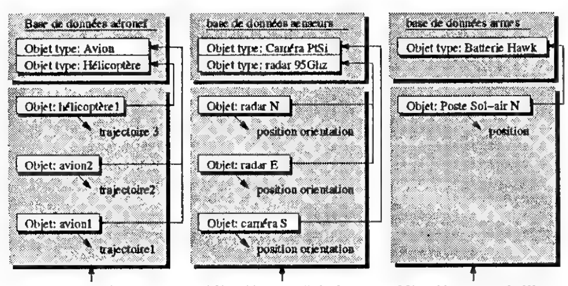

Figure 1 : Chaînage des informations

L'intérêt de cette structuration réside dans sa maniabilité, tant pour la gestion des situations que pour leur visualisation. En effet, chaque objet type est représenté à l'écran par un symbole. Par exemple, un RADAR de surveillance est figuré par un secteur angulaire blanc,

dont l'angle au sommet est égal à la couverture azimutale de l'antenne. Un POSTE RADAR est un secteur angulaire blanc, positionné et orienté (sur l'image numérisée du terrain si celle–ci est disponible). Enfin, une CONSTELLATION DE SENSEURS est une répartition de secteurs blancs et rouges (pour distinguer les radars des imageurs thermiques).

L'opérateur a la possibilité de modifier interactivement (au moyen de la souris) une constellation de capteurs (et de sauvegarder la nouvelle, si celle–ci s'avère intéressante après analyse). En particulier, il peut :
– SUPPRIMER un capteur de la constellation si celui–ci semble inutile.
– ACTIVER–DÉSACTIVER un capteur pour simuler une défaillance du système.
– DÉPLACER un senseur.
– AJOUTER et positionner un capteur de la base de données
Toutes ces démarches s'appliquent aux méta–objets MOYEN DE DÉFENSE.

La Figure 2 (image d'écran, première version du logiciel) représente une situation terrestre dans le plan horizontal. Une image numérisée de la zone de surveillance étant disponible, elle est utilisée comme fond d'écran et guide l'opérateur dans ses démarches (Il est en outre possible d'utiliser l'image altimétrique du terrain).

Figure 2 : Représentation d'une situation terrestre

L'échelle de visualisation est choisie par l'utilisateur (on pourra par exemple zoomer sur une zone). L'image 2 représente une superficie de 8km sur 7,5km sur laquelle sont disposés une base sol–air (carré rouge), cinq points sensibles (carrés blancs), trois radars de veille (secteurs blancs) et deux imageurs thermiques (secteurs rouges). Remarquons qu'un des radars est co–localisé avec un imageur. Il est aussi possible de visualiser le réseau de communications et les processeurs de fusion.

3.3 Les senseurs

Bien que le logiciel développé ne constitue nullement un Système Expert, il est clair que la conception d'un système multi–capteurs doit impliquer une certaine hiérarchisation des senseurs en fonction de leur utilisation nominale. (Il sera sans doute, par la suite, très profitable de coupler l'outil ROSACE avec un Système Expert afin de guider l'opérateur dans son choix d'objets type.) L'analyse ci–dessous permet d'orienter la construction de la base de données pour les objets type SENSEUR. L'étude se limite à l'utilisation de deux types de capteurs, les radars et les imageurs thermiques. On trouvera une présentation générale de divers types de capteurs dans [1].

En ce qui concerne le choix des radars, dans le cadre de la surveillance et de la défense anti–aérienne, on adoptera essentiellement des radars centimétriques (les radar millimétriques ne sont pas vraiment appropriés) pour la veille, la détection, la poursuite et la reconnaissance de menaces.

– Les radars centimétriques en bandes L et S (fréquence entre 1 GHz et 4GHz) sont consacrés à la veille grande et moyenne portée. On leur préfère en général les radars en bandes C et X (de 4 à 12.5 GHz) pour les Systèmes d'Armes à Courte Portée, par ailleurs plus adaptés à la poursuite. Citons pour la veille 2D haute altitude, le radar ANTARES, ou la famille des TRS 2054, et pour la surveillance basse altitude, le radar Doppler RAMSA, fabriqués par la firme Thomson. Pour la poursuite multi–cibles on pourra considérer le radar ATLAS (haute altitude) qui fonctionne en bande C, ou le radar LOUXOR (basse altitude) ou encore RODEO (Dassault).
Les mesures fournies par ces capteurs, lorsqu'une cible a été détectée, sont :
(1) la distance R de la cible ainsi que sa vitesse radiale $\dot{R}$ (radar Doppler), avec une précision assez fine puisque les erreurs sont typiquement de l'ordre de 5m pour R et de 1 m/s pour $\dot{R}$.
(2) son azimut φ avec une précision médiocre de l'ordre du degré. Si le radar est 3D (balayage généralement électronique), la déclinaison est aussi indiquée.
(3) la Section Efficace Radar (SER) de la menace.

La longueur d'onde de l'émission électro–magnétique variant entre 2cm et 30cm, elle est nettement supérieure à la taille des gouttes de pluie, des particules de brouillard ou de fumée. Ceci rend les radars centimétriques très peu sensibles aux conditions atmosphériques. Par contre, ils demeurent très sensibles au brouillage et facilement décelables par l'ennemi.

– Les radars millimétriques émettent essentiellement à 35 et 95 GHz car à ces fréquences, l'atténuation atmosphérique est faible.
Ils fournissent des mesures de R, $\dot{R}$ et φ avec de bonnes précisions typiquement de l'ordre de 1 m, 0,1 m/s et 0.5° respectivement, des valeurs de SER et de polarisation.

Ils sont peu encombrants (mais coûteux), peu sensibles aux contre-mesures. Par contre, leur efficacité est réduite par temps de pluie.

Les imageurs thermiques sont des senseurs passifs (donc plus discrets que les radars) qui permettent théoriquement la détection et la reconnaissance d'objets. Ils fournissent des mesures d'émission IR (liée par l'émissivité à la température du "corps noir"), et de position angulaire avec des précisions tout à fait satisfaisantes puisque les erreurs sont inférieures au milliradian.
Ces senseurs fonctionnent dans deux bandes de longueur d'onde :
– la bande 3–5 µm pour la détection d'objets chauds tels des autodirecteurs de missiles, tuyères d'engins...
– la bande 8–12µm pour des objets à température ambiante.
Ce choix est imposé par l'existence de "fenêtres atmosphériques" qui font que l'atténuation atmosphérique est tolérable à ces longueurs d'onde.
La portée de ces imageurs est de l'ordre de quelques km, mais est fortement dégradée par le brouillard, les nuages, les contremesures (aérosols et fumigènes). La couverture en azimut est souvent de 360°. Citons l'exemple du système VAMPIR.

La complémentarité des senseurs apparaît évidente :
– Les mesures de distance et d'angles combinées astucieusement, pourront permettre de déduire la position d'une cible dans l'espace 3D.
– La connaissance conjointe de l'émission IR d'un objet et de sa SER, contribue à une meilleure identification.
– Certaines conditions atmosphériques ou contremesures dégradent le fonctionnement d'un type de capteur et demeurent sans effet sur un autre type.

4. PERFORMANCES OPTIMALES DU SYSTÈME

La configuration multi-capteurs est évaluée selon trois critères. Les calculs sont détaillés dans [2].

4.1 Couverture du système

Le problème est de déterminer la région de l'espace dans laquelle un aéronef (d'un type donné par sa SER ou son émission IR) est détecté *presque sûrement* par le système.

L'approche la plus simple, pour aborder ce problème est la suivante : considérons un aéronef situé en un point (x,y,z), de l'espace (à un instant donné). Nous cherchons à savoir si cet engin est *visible* par au moins un des capteurs du système à un instant quelconque.
Par exemple, si un radar se trouve en (x_r, y_r, z_r) avec l'axe de rotation Y de l'antenne défini comme sur la Figure 3 par les angles (Ω,θ), on peut déduire la distance R de l'engin, son azimut φ et sa déclinaison δ par les relations :

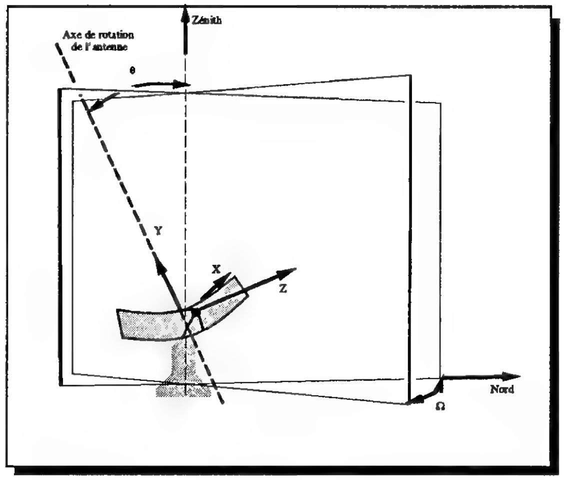

Figure 3 : Orientation d'un radar, repère radar

$$\boxed{\begin{array}{l} R = \sqrt{X^2+Y^2+Z^2} \\ \varphi = \mathrm{Arctg}(X/Y) \\ \delta = \mathrm{Arctg}(Z/\sqrt{X^2+Y^2}) \end{array}} \qquad (1)$$

avec,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \sin\theta \end{bmatrix} \begin{bmatrix} \cos\Omega & \sin\Omega & 0 \\ -\sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x-x_r \\ y-y_r \\ z-z_r \end{bmatrix} \qquad (2)$$

L'équation du radar permet d'approximer le rapport signal-à-bruit S/N en fonction des paramètres de la cible et de ceux du radar. Par conséquent, en appliquant un test de détection simple [3] sur le premier lobe d'antenne, par seuillage du rapport siganl-à-bruit, il est possible de savoir si la probabilité de détecter l'aéronef situé en (x,y,z) est supérieure à une certaine valeur. La probabilité de fausse alarme est fixée préalablement. On dira que l'engin est *visible* par le radar dans l'affirmative. Notons que l'antenne d'un radar de surveillance effectue une rotation entre φ_{min} et φ_{max} dont il faudra tenir compte. D'autre part même pour un radar 2D, l'ouverture en déclinaison (premier lobe d'antenne) doit être intégrée aux calculs.
L'opération étant faite pour toutes les positions (x,y,z) de l'espace, on détermine ainsi la région couverte par le capteur.
La *couverture* du système sera donc ici assimilée à la juxtaposition des couvertures individuelles.
Deux remarques s'imposent :
– Le test de détection employé peut être perfectionné selon la précision des résultats requise. Par exemple, dans le cas de la détection radar, la SER de l'engin pourra être modélisée par différentes distributions de probabilité. Un test de détection du style Neymann–Pearson pourra alors être élaboré. De plus, la détection pourra se faire sur le lobe principal d'antenne ou aussi sur les lobes secondaires.
– A ce stade, on peut déjà exploiter le réseau de communications et voir si des tests de détections multi-capteurs ([2] & [4]) ne peuvent pas être utilisés pour augmenter la couverture. Dans [4], on étudie quatre tests de détection multi-capteurs : deux tests bas débit optimaux (test "ou", test "et") pour lesquels une décision

centralisée est prise à partir des décisions individuelles, le test linéaire optimal qui compare à un seuil une combinaison linéaire des énergies reçues par chaque capteur, et enfin le test optimal (toujours centralisé) qui compare un rapport de vraisemblance conjointe à un seuil. Ce seuil est calculé en fonction des performances requises pour le système global (probabilité de fausse alarme pour le système). Une comparaison de ces tests a été menée afin de quantifier l'apport de chacune des méthodes de *fusion*. L'implémentation de ces tests au sein du logiciel ROSACE est en cours. La Figure 4 illustre ce point : dans le cas simple où les informations délivrées par deux capteurs (1 radar et un imageur ici) sont fusionnées pour la détection, la probabilité de détection du système des deux capteurs peut être évaluée en fonction des $(S/N)_1$ et $(S/N)_2$ pour chaque capteur. Les résultats sont présentés sous forme de réseau de courbes, P_d en fonction de $(S/N)_1$ avec $(S/N)_2$ constante. La probabilité de fausse alarme du système a été fixée à 10^{-5}. Les modélisations des signaux sont classiques [3].

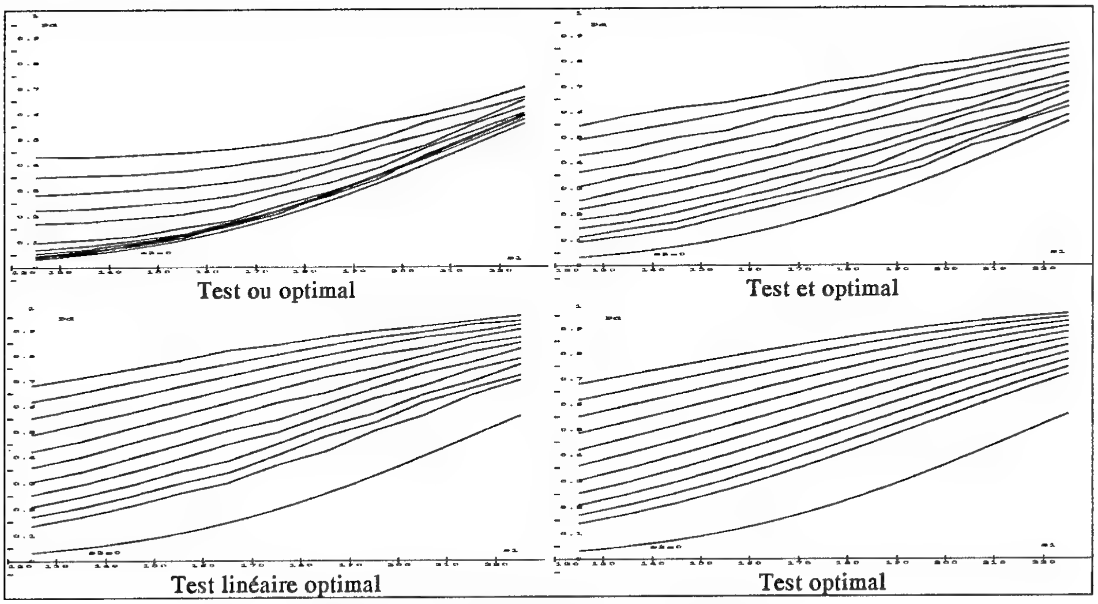

Figure 4 : Performances des tests de détection

La visualisation de la *couverture* des capteurs proposée ici, est faite par plan d'altitude relative z=constante. L'altimétrie du terrain, qui peut masquer certaines zones, est prise en compte pour ces calculs.

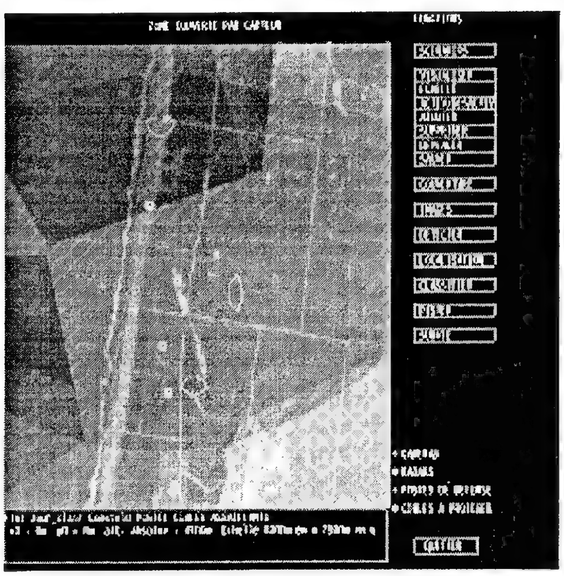

Figure 5 : Couverture du système à z=4500m

Ce premier calcul permet de juger de la bonne disposition des capteurs sur le terrain. D'autre part, si l'on applique des tests de détection multi–capteurs, on pourra connaître l'impact du réseau de communications.

4.2 Zones de localisation et précision sur les mesures

La région de *localisation* est définie comme la région sur laquelle la position 3D d'un engin peut être déduite. Rappelons que la plupart des capteurs utilisés ici sont des capteurs 2D. Les radars délivrent des mesures de distance et d'azimut, les imageurs thermiques des mesures de site et gisement. Par conséquent un aéronef situé dans la zone couverte par le système (la couverture étant définie par l'opérateur comme indiquée plus haut) n'est pas forcément localisable. C'est–à–dire que même dans les conditions les plus favorables, la position 3D de l'engin ne peut être obtenue.

Un raisonnement simple va permettre de déterminer la région de localisation. Il est clair que l'aspect temporel (synchronisme des mesures, délai de transmission) n'est pas pris en compte ici comme dans tout ce paragraphe. Les mesures de position délivrées par les capteurs sont entachées d'une erreur. Celle–ci est modélisable par une densité de probabilité de présence, gaussienne 2D centrée sur la mesure et dont la variance peut s'exprimer en

fonction des caractéristiques du capteur et du rapport S/N. Par exemple pour un radar à impulsions les écarts-type sur R et φ sont donnés par :

$$\boxed{\begin{aligned}\sigma_R &= \frac{C\tau}{4\sqrt{S/N}}\\ \sigma_\varphi &= \frac{\Delta\varphi}{2\sqrt{S/N}}\end{aligned}} \qquad (3)$$

où C désigne la vitesse de la lumière et $\Delta\varphi$ l'ouverture du premier lobe d'antenne.

La densité de probabilité de présence en (x,y,z) d'un engin, est le produit des densités de probabilité de présence 2D délivrées par chacun des capteurs (en supposant que chacun ait détecté l'engin en (x,y,z)). Dans certains cas (em paritculier dans les régions couvertes par au moins deux capteurs) on obtient ainsi une densité gaussienne tridimensionnelle. Ces calculs sont justifiés dans [2]. Notons qu'ils sous-entendent des hypothèses de linéarisation du tore d'erreur pour les radars, qui ne sont pas toujours satisfaites.

La matrice de covariance de la densité obtenue par *fusion* des densités individuelles, correspond en fait à la précision maximale que l'on peut attendre sur les mesures de localisation.

Pour chaque point (x,y,z) de l'espace, on calcule la matrice de covariance de la densité de probabilité de présence 3D. Si celle-ci existe, l'aéronef est localisable, sinon sa position est indéterminée par le système. La trace de la matrice est une norme simple et donne une idée de la précision du positionnement.

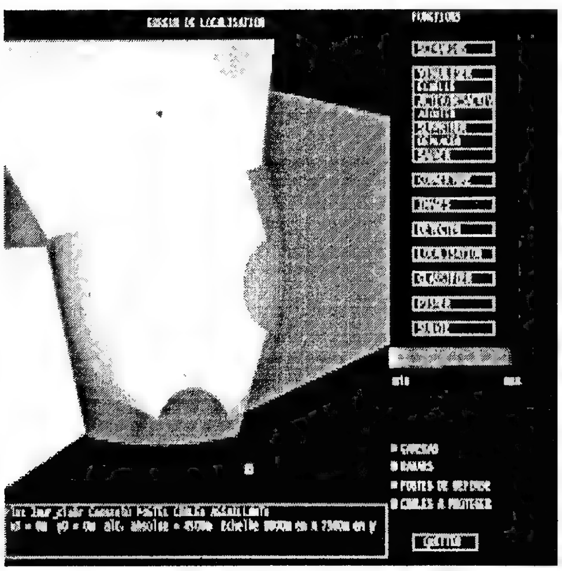

Figure 6 : Précision sur la localisation

Ces calculs permettent de porter un jugement sur la disposition des capteurs sur le terrain. Signalons qu'ils pourraient être effectués par sous-groupes de capteurs. Ainsi une seconde évaluation du réseau de communications serait fournie puisque l'on connaîtrait les capteurs qui coopèrent et se complètent réellement.

Notons que le problème de localisation qui consiste à retrouver les coordonnées d'un engin à partir des mesures, est plus complexe et s'assimile en fait au problème de poursuite.

4.3 Vulnérabilité d'une menace

Les calculs de *couverture* et de *localisation* permettent de porter un premier jugement quant à la disposition des capteurs sur le terrain et à l'impact du réseau de communications. Il est aussi possible dans le cas où le système assure la défense, de porter un jugement sur l'efficacité et la répartition des systèmes d'armes. Pour illustrer simplement ce point, considérons le cas d'une plate-forme de tir d'obus anti-aériens située en (x_a,y_a,z_a). L'aéronef étant modélisé par un ellipsoïde dont les axes sont déterminés en fonction des caractéristiques de l'engin, la probabilité d'impact d'un ou de N obus sur l'engin situé en (x,y,z) (avec une densité de probabilité de présence calculée au 4.2), peut se déduire. On supposera le système figé, (pas de délais, aéronef fixe).

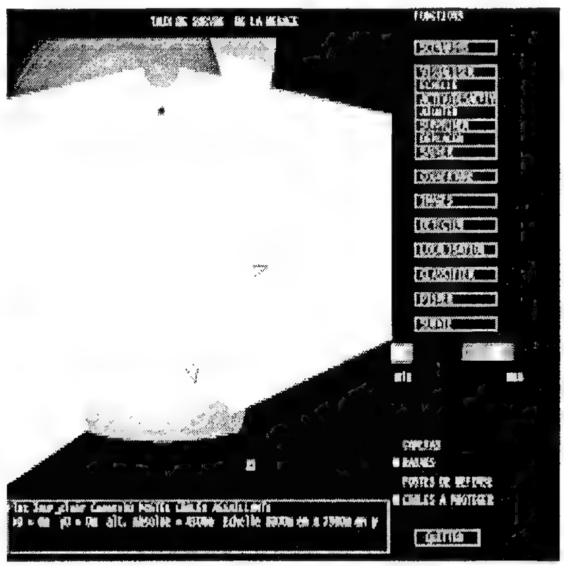

Figure 7 : Vulnérabilité d'un aéronef à z=4500m

D'autres critères pourront être envisagés pour qualifier le fonctionnement du système multi-capteurs. Notament il serait intéressant de mener un calcul de vulnérabilité du système ou de probabilité de destruction face à une menace ennemie.

5. CHOIX ET ANALYSE D'UN SCÉNARIO

Une situation ou un système de surveillance étant défini, il est possible de confronter ce système à différents scénarii, et d'analyser ainsi son efficacité ou sa fiabilité.

5.1 Spécification d'un scénario

Un scénario est spécifié par, d'une part des conditions atmosphériques (température, pression, hydrométrie ...) et d'autre part la mission aérienne.

L'opérateur a alors la possibilité d'utiliser l'éditeur de trajectoires intégré au logiciel ROSACE. Il définit interactivement les trajectoires d'un certain nombre d'aéronefs dans le plan horizontal (x,y). Ensuite, il trace l'altitude z en fonction du temps.

L'opérateur peut visualiser, grâce au synthétiseur d'images radars et infrarouges intégré au logiciel ROSACE, les cartes radars (énergie reçue par le radar en fonction de R et φ) ou les cartes thermiques à un instant donné. Celles-ci pourront par exemple être exploitées pour la classification et le dénombrement des aéronefs.

5.2 Analyse

L'analyse du scénario s'effectue en quatre étapes extrêmement corrélées mais que l'on peut néanmoins classer par ordre de complexité croissante :

Le problème fondamental est celui de la *détection* des aéronefs lors de la mission. Au niveau de chacun des processeurs de fusion, l'opérateur pourra choisir parmi plusieurs tests proposés selon la configuration du système (et, ou, linéaire, optimal). Ici, contrairement au paragraphe 4, les énergies des signaux sont simulées à partir de modèles et de générateurs de bruit. Si des mesures réelles d'énergie, ou des images, étaient disponibles, on les utiliserait pour appliquer les tests de détection.

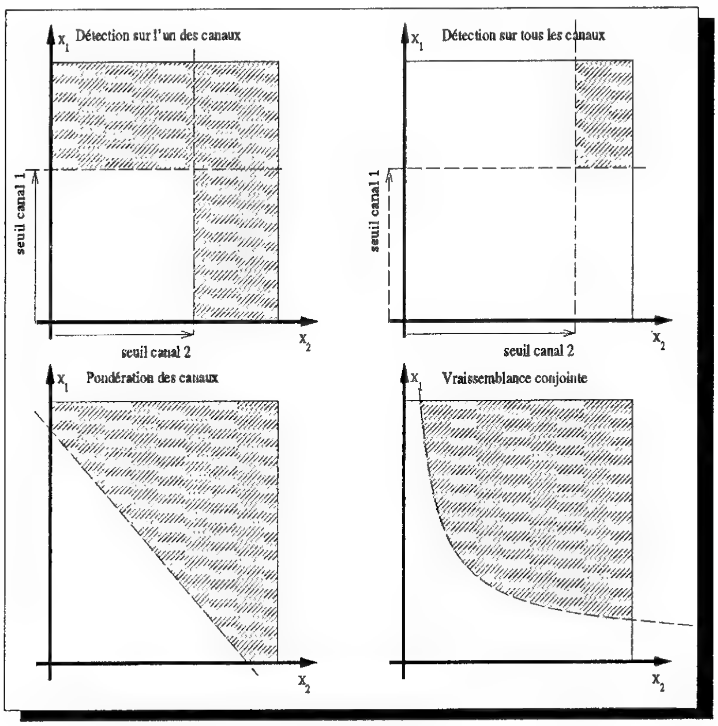

Figure 8 : Tests de détection pour deux capteurs

Par exemple, si l'on considère des tests de détection bimodes (fusionnant les informations délivrées par deux capteurs), on trouve dans [4] l'allure des régions de décision pour les quatre tests mentionnés ci–dessus (Figure 8).

Le *pistage* s'effectue par des traitements du style filtrages de Kalman ou PDAF [5] et est évidemment affecté par les résultats de la détection.. D'autres algorithmes sont en cours d'étude.

La fusion des informations se fait soit au niveau des mesures délivrées par chaque capteurs (*fusion des plots*), soit au niveau des estimations issues de traitements individuels (*fusion des pistes*), selon la structure et les capacités du réseau de communications. Notons que le premier type de fusion permet d'exploiter avantageusement les calculs de précision de localisation développés au paragraphe 4.

Les délais de transmission [capteur ⟶ processeur de fusion], ainsi que l'asynchronisme des mesures ou des estimations sont prises en compte.

D'autre part, le problème de l'allocation des ressources qui consiste à attribuer à un groupe de capteurs la tâche de poursuivre un ensemble de cibles, devrait être résolu à ce stade mais est encore à l'étude.

Enfin les problèmes de *classification* (hélicoptère, avion, missile), et de *dénombrement* étant très complexes, seule une ébauche en a été faite, dans laquelle la théorie de l'évidence [6], extension de la théorie bayésienne, est appliquée.

La quatrième étape de l'analyse consiste à consigner les résultats de réussite ou d'échec (pour la détection, la poursuite, la classification) correspondant à un scénario. Il s'agira d'effectuer des statistiques sur un certain nombre de missions afin de mesurer l'efficacité du système multi-senseurs.

6. CONCLUSION

Le logiciel ROSACE qui est en cours de développement à l'O.N.E.R.A. est un outil d'aide à la conception de systèmes de surveillance ou de défense anti-aérienne multi-senseurs. L'originalité de cet outil est que l'optimisation du système comprend non seulement le choix des capteurs et leurs positionnement sur le terrain, voire leur mode de fonctionnement, mais aussi le choix judicieux des méthodes de traitements. Ces algorithmes souvent originaux font appel à la *fusion d'informations* et améliorent les performances et l'efficacité du système.

Une première analyse globale a été proposée qui permet de juger de la bonne configuration géométrique du système multi-senseurs, c'est-à-dire de la disposition des capteurs et des systèmes de défense sur le terrain, et de l'impact du réseau de communications. La *couverture*, la *région de localisation* et enfin la *vulnérabilité d'un aéronef* ont été définies et visualisées. Notons que le dernier calcul pourra par la suite être remplacé par un calcul de *vulnérabilité du système* face à une menace aérienne.
En second lieu, le module de simulations permet de confronter le système à des scénarii choisis par l'opérateur. Des statistiques sur la réussite ou l'échec du système pour accomplir les tâches de *détection*, *pistage*, ou *classification* pourront être faites. Ainsi l'optimisation du système multi-senseurs devra prendre en compte non seulement les résultats de l'analyse globale mais aussi ceux des simulations.

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MULTISENSOR DATA FUSION FOR INTEGRATED MARITIME SURVEILLANCE

A. Premji and A. M. Ponsford
Raytheon Canada Limited
400 Phillip Street
Waterloo, Ontario
Canada, N2J 4K6

1 SUMMARY

A prototype Integrated Coastal Surveillance system has been developed on Canada's East Coast to provide effective surveillance out to and beyond the 200 nautical mile Exclusive Economic Zone. The system has been designed to protect Canada's natural resources, and to monitor and control the coastline for smuggling, drug trafficking, and similar illegal activity.

This paper describes the Multiple Sensor - Multiple Target data fusion system that has been developed. The fusion processor has been developed around the celebrated Multiple Hypothesis Tracking algorithm which accommodates multiple targets, new targets, false alarms, and missed detections. This processor performs four major functions: plot-to-track-association to form individual radar tracks, fusion of radar tracks with secondary sensor reports, track identification and tagging using secondary reports, and track level fusion to form common tracks.

Radar data from coherent and non-coherent radars has been used to evaluate the performance of the processor. This paper presents preliminary results.

2 INTRODUCTION

This paper describes a general purpose Multisensor Multitarget (MSMT) fusion processor that has been developed around the Multiple Hypothesis Tracking (MHT) algorithm.

The processor has been developed for use in the Raytheon Canada Limited (RCL) Integrated Maritime Surveillance (IMS) system that uses long range surface wave radars to detect targets on and above the ocean surface out to and beyond the 200 nautical mile Exclusive Economic Zone (EEZ).

The MSMT processor uses MHT to form local tracks for each radar sensor. Adjunct sensor information is then used where available to identify tracks provided by the MHT. Local tracks from multiple radars are fused to form global tracks.

The MSMT processor is implemented using a modular software development strategy in a pure object-oriented environment resulting in a highly flexible development that permits rapid modification and extension. This is reflected in the flexible nature of the processor which can be used for coherent radar (providing range, range rate, and azimuth) as well as non-coherent radars (providing range and azimuth).

Real as well as simulated data is used to assess the performance of the processor for airborne targets. The focus of the performance assessment is multiple target tracking (MTT) for both coherent and non-coherent radar.

3 INTEGRATED MARITIME SURVEILLANCE

The Integrated Maritime Surveillance (IMS) system provides continuous, all weather surveillance of the 200 mile Exclusive Economic Zone (EEZ). The shore based system, illustrated in Figure 1, detects, tracks, and identifies aircraft and ships throughout the EEZ. The IMS comprises four principle elements.

3.1 Long Range Surface Wave Radars

Radar coverage of coastal waters has traditionally been limited to line of sight from the radar antenna and is an inherent characteristic of radar systems operating at microwave frequencies. Radars operating at the lower end of the High Frequency band (3 MHz to 6 MHz), that use the surface wave mode of propagation follow the curvature of the earth and can detect targets hundreds of kilometers beyond the horizon. Surface Wave Radars (SWR) are coherent and provide target range, azimuth, and range rate.

3.2 Automatic Dependent Surveillance Systems

Aircraft and vessels equipped with Automatic Dependent Surveillance (ADS) systems transmit identification and position information on a regular schedule over a pre-assigned communications channels to a shore based tracking system.

3.3 Adjunct Sensors

Adjunct sensors are the systems that traditionally provide surveillance and include communications, mandatory reporting procedures as well as visual identification from patrol vessels and aircraft. These sensors reports are characterized by their infrequent and often tardy nature.

3.4 Multisensor Data Fusion

The data fusion system automatically correlates tracks derived from the long range radar sites with ADS tracks and target attributes obtained from communications and other identification systems.

4 MULTISENSOR MULTITARGET PROCESSOR

The track processor must accommodate multiple targets, crossing targets, spurious detections, and missed detections. Events of confusion manifest themselves in the report to track assignment procedure and lead to association uncertainty. Since the events are short lived, the resulting association confusion can be better combatted by deferring assignment decisions until additional scans of information are available. This allows association conflicts to be resolved by exploiting the correlation inherent in target dynamics.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

MHT combats association confusion by postulating a predefined number of hypotheses (partitions of reports into tracks) and propagating the resulting tracks till a decision can be made with greater confidence. In the interim, conflicting assignments that cannot be resolved immediately are carried in the multiple partitions. One of the major hurdles to the acceptance of MHT as a viable solution for multiple target tracking (MTT) has been the attendant computational requirements. As shown in this exposition, recent algorithmic advances and advances in computational speed make MHT practical on a general purpose PC.

The MSMT processor is also required to perform the additional task of sensor integration or fusion. For the IMS system the MSMT processor performs fusion at the track level. A discussion of the sensor fusion approach for the IMS is provided later. The overall MSMT processor including the MHT algorithm and the sensor fusion processing is shown in Figure 2.

4.1 Multiple Hypothesis Tracking

It is widely accepted that MHT provides the best tracking performance amongst all MTT techniques aside from batch processing [3]. However, batch processing requires retaining data over multiple scans and performing the processing over the entire batch of reports.

The MHT algorithm developed is a variant of the MHT as originally reported in [1]. It includes all procedures of the original algorithm required to make the algorithm practical: track gating, cluster management (formation, splitting, combining, deletion), hypotheses management for each cluster (updating, combining, deletion, pruning), and track management (predicting, updating as per the hypotheses, promotion, deletion, combining). As suggested in the literature [2, 3], judicious application of these procedures produces track performance that is comparable to the optimum performance for MHT.

The fundamental entity in the MHT algorithm is a cluster comprising a track list and a hypothesis list. Each cluster is characterized by a set of hypotheses (arranged in descending order of likelihood). Each hypotheses maintains its likelihood (or hypothesis score) and a set of pointers to elements in the track list. Each element in the track list is an object that maintains all the required track characteristics (the Kalman filter characteristics, track score, track life stage, track length, number of updates, number of consecutive misses, last N reports smoothed, track label, etc.).

Figure 3 shows the processing steps for the current set of clusters and a single scan of reports. The first step is the clean up procedure: remove deleted tracks from the track list, renumber tracks in the list, adjust hypothesis track pointers, delete empty hypotheses and clusters. Next, the remaining tracks for all clusters are gated with the current scan of reports and the track-report association likelihoods computed. A two stage gating procedure (a coarse gate applied first) reduces computation considerably.

The basic steps for calculating the association likelihoods or probabilities are discussed in [4, 5]. An assumption invoked there is that tracks hypothesized from the previous scan are equi-probable. Although this assumption leads to simplifications in the association probability calculation, it entails discarding information that is available. Specifically, the MHT algorithm proposed here maintains a score and status for each track which provides a-priori track information. The modifications to the derivations in ([5] equation 7) are as follows:

Assume that after processing the previous scan of reports the aggregate number of tracks is K. The a-posteriori probability of track i conditioned on report j is given by:

$$P(T_i/z_j) = \frac{p(z_j/T_i)\,p(T_i)}{\sum_K p(z_j/T_k)p(T_k)} \tag{1}$$

If it is assumed that the a-priori target probabilities are equal ($p(T_k) = p(T) \quad \forall k$), then equation (7) in [5] follows. Since a-priori track information is available it can be used to develop a more precise likelihood calculation. Using the normalization procedure suggested in [4] and continuing the development therein provides the association likelihood for the j-th report and the i-th track, thus:

$$P_D(T_i) \quad \frac{\exp(-d_{ij}^2/2)}{\beta(2\pi)^{M/2}\sqrt{|S_{ij}|}} \quad P(T_i) \tag{2}$$

where S_{ij} is the residual covariance matrix for track i and report j, β is the combined spatial density of new targets and false alarms, $P_D(T_i)$ is the probability of detection for track i, and d_{ij}^2 is the normalized square distance for the i-th track and the j-th report. For further details see [1, 3, 5].

The above extension for the likelihood computations in [4,5] provides a means for including the a-priori track likelihood as well as the probability of detection for each track. Since the latter is not available for each individual track, it is assumed to be independent of the specific track and is set to the nominal radar probability of detection. The report-track association likelihoods (or log-likelihoods) are determined using equation (2) to provide a likelihood matrix for all tracks and all reports.

The likelihood matrix defines the association problem for the current scan of reports. This matrix is analyzed to determine sets of report numbers gated by each track. Analysis of set intersections for all tracks in all clusters indicates the nature of the association problem for the current scan. This provides the basis for re-clustering the association problem, splitting unassociated clusters and merging associated clusters. To this point the processing has been predominantly of a database management nature aside from the calculation of track-report association likelihoods.

The next step determines the N-best hypotheses for each cluster given the current scan of reports and the previous hypotheses. An efficient method for finding the N-best hypotheses is a key element in making pruned MHT practical. Traditional methods are encumbered with the need to consider all hypotheses extensions in order to find the N-best. The total number of hypothesis extensions can be very large, causing brute force search techniques to be extremely time consuming.

A novel constrained search technique proposed in [6] provides a means of finding the required hypotheses by considering only a small subset of the total number of extension hypotheses. This reduction is facilitated by structuring the search so that rejection of a single hypothesis (when it doesn't make the N-best list) excludes many other inferior hypotheses from consideration. In this way the more unlikely hypotheses (of which there are many) are never considered and processing times are dramatically reduced.

The constrained search technique requires repeated solution of the assignment problem. A technique proposed in [6] is the Jonker-Volgenant (JV) algorithm. Comparisons of a number of solutions for the assignment problem in [7] indicates that the Auction solution is faster than the JV algorithm and has been implemented in the N-best constrained search for the MHT algorithm.

The extended hypotheses indicate the N-best ways to associate the current scan of reports with previous tracks. All the tracks postulated by these hypotheses are now updated with the assigned reports. In addition, reports that are postulated to be from new targets are used to initiate single point (potential) tracks. False targets are considered as new targets that are later deleted so they need no special consideration. The processing cycle for the current scan of reports is now complete.

4.2 Track Filtering

The MSMT system supports coherent and non-coherent radar sensors. Coherent sensors will provide measurements of range, azimuth, and range rate, whereas non-coherent sensors will only provide range and azimuth. The implementation of both Kalman filters is discussed here with emphasis on the unique approaches adopted to improve processing speed. Both filters are fully coupled two dimensional Kalman filters with components of the Kalman computations performed in the most suitable coordinate system. Currently the MSMT processor accomodates only a single level of target manoeuvre, although work is in progress to detect target manoeuvres and adapt the filter process noise.

In the case of a coherent sensor both the computational load and the requirement to include range rate measurements dictate the choice of the coordinate systems, whereas for non-coherent sensors the driving factor is the computational load.

Figure 4 shows the Kalman computations for coherent radar reports and the coordinate systems used to perform the calculations. Intermediate steps in the following derivations use standard coordinate transformations. The predicted state vector in antenna cartesian coordinates (ACC) is given by:

$$\tilde{s}_a = [x \quad \dot{x} \quad y \quad \dot{y}]^T \tag{3}$$

where T signifies matrix transpose. Let $\tilde{P}_a$ denote the corresponding prediction covariance. Initially $\tilde{s}_a$ is transformed into the track line of sight cartesian coordinate (TLOSC) system, which is the ACC rotated by the track prediction azimuth angle, to get $\tilde{s}_{tc}$ and $\tilde{P}_{tc}$. Track-report association is performed in the track line of sight polar coordinate (TLOSP) system. The track prediction in TLOSP is given by

$$\tilde{s}_{tp} = [\tilde{s}_{tc}(1) \quad 0 \quad \tilde{s}_{tc}(2)]^T \tag{4}$$

where the ordering is range, azimuth, and range-rate. Let the measurement rotated into the TLOSP be given by s_m, then the normalized square distance for track i and report j is:

$$d_{ij}^2 = (\tilde{s}_{tp,i} - s_{m,j})\, S_{ij}^{-1}\, (\tilde{s}_{tp,i} - s_{m,j}) \tag{5}$$

where the residual covariance matrix is:

$$S_{ij} = (J_i \quad \tilde{P}_{tc,i} \quad J_i^T \quad + \quad P_m) \tag{6}$$

where P_m is the standard diagonal radar measurement variance matrix and the jacobian (evaluated at the track prediction is):

$$J_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1/\tilde{s}_{tc,i}(1) & 0 \\ 0 & 1 & \tilde{s}_{tc,i}(4)/\tilde{s}_{tc,i}(1) & 0 \end{pmatrix} \tag{7}$$

Note that (6) is independent of the specific measurement, j, and consequently the matrix inversion in (5) is performed only once per predicted track.

The Kalman smoothing equations (omitting track and measurement indices) are:

$$\hat{s}_{tc} = \tilde{s}_{tc} + K\,[s_m - \tilde{s}_{tp}] \tag{8}$$

$$\hat{P}_{tc} = [I - K\,M]\,\tilde{P}_{tc} \tag{9}$$

where the Kalman gain is determined using:

$$K = \tilde{P}_{tc}\, M^T\, [M\, \tilde{P}_{tc}\, M^T + P_m]^{-1} \tag{10}$$

and the measurement matrix is:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & \tilde{s}_{tc}(4)/\tilde{s}_{tc}(1) & 0 \end{pmatrix} \tag{11}$$

Non-coherent radar reports are processed using the standard Kalman equations [3] in ACC. The normalized square distance calculation for association purposes is calculated in TLOSP as in equation (5), where now

$$\tilde{s}_{tp} = [\tilde{s}_{tc,i}(1) \quad 0]^T \tag{12}$$

and the radar measurement rotated into TLOSP, s_m, includes only range and azimuth. The residual covariance matrix is given by

$$S_{ij} = [J_{1,i} \quad \tilde{P}_i \quad J_{1,i}^T \quad + \quad P_m] \tag{13}$$

where P_m is the measurement variance matrix for range and azimuth,

$$\tilde{P}_i = \begin{pmatrix} \tilde{P}_{tc,i}(1,1) & \tilde{P}_{tc,i}(1,3) \\ \tilde{P}_{tc,i}(1,3) & \tilde{P}_{tc,i}(3,3) \end{pmatrix} \tag{14}$$

$$J_{1,i} = \begin{pmatrix} 1 & 0 \\ 0 & 1/\tilde{s}_{tc,i}(1) \end{pmatrix} \tag{15}$$

It is evident from the preceding equations that many of the matrices are very sparse. The implementation of all Kalman related computations fully exploits this sparseness to reduce computation requirements.

4.3 Track Fusion

There are two methods for combining data from multiple sensors, sensor level fusion and track level fusion. Sensor level fusion combines reports from multiple sensors directly into global tracks. Track level fusion processes reports from each individual sensor to form local tracks which are subsequently combined into global tracks.

Track level fusion results in reduced processor complexity and provides inherent robustness against single site failures due to decentralized processing [3]. Although sensor level fusion provides more accurate track information (under some circumstances), the improvement is small [8] and the resulting complexity is significant. Fusion for the MSMT system is performed at the track level.

Local tracks are first time aligned (predicted) to a common fusion time and transformed into a global coordinate system. Next the processor assesses track similarity by applying coarse tests on kinematic quantities such as position, speed and heading. Tracks that pass the coarse similarity tests are subject to a likelihood calculation (similar to the calculation in equation (2)). Track similarity is determined by thresholding this likelihood.

Tracks passing the likelihood threshold test are then fused using a modified Kalman filter [9]. The filter combines individual track states and covariances into a single track for presentation. Tracks failing the track similarity test are presented as separate tracks.

5 TRACK PROCESSOR EVALUATION

The performance of the MHT implementation is tested for both coherent and non-coherent radar data. Use of simulated radar data provides the opportunity to setup controlled tracking scenarios of interest. Use of real radar data adds credibility to the performance of the tracker for real world situations.

5.1 Simulation Results

The scenario is a simulation of 9 targets, 2 manoeuvring. The simulation was run for 500 updates with an update interval of 300 seconds. Simulated sensor measurement error (one standard deviation) are typical of SWR: range 0.25 km, azimuth 0.2 degrees, and range rate 0.2 m/s. Five hypotheses are retained after each scan. Target velocities range from 4 to 10 knots.

Figure 5 plots the resultant tracks, with life stage tentative or better. The upper plot shows all hypotheses. Considerable confusion can be seen to result. The lower plot, which displays only the best hypothesis, shows that the MHT algorithm correctly maintains all tracks inspite of the association confusion.

The MHT algorithm is currently implemented in Smalltalk on a 486/33 MHz PC. As an example of the processing speed, when configured to retain the 5-best hypotheses per cluster per scan the algorithm can process approximately 80 detections in real time at a scan update rate of 10 seconds. Clearly, this performance can be improved considerably on a faster machine.

For example, the SPARC-10 provides a speed-up factor in excess of 10 times compared to the 486/33. Now the processing burden will increase approximately linearly with an increase in the number of detections if the cluster sizes remain unchanged and only the number of clusters increase. This suggests that a factor of 10 speed-up will allow processing in the region of 800 detections (assuming a 10 second radar scan time). An increase in the scan rate will lead to a proportional decrease in the number of detections that can be processed.

5.2 Cold Lake Data

The radar data for this assessment was provided by the Defence Research Establishment Ottawa (DREO), Canada. Data gathering took place during the Raid Tracking Trials (RATT) at Canadian Forces Base, Cold Lake, Alberta, in September 1986. The radar (5 second scan rate) measurement errors are: range 0.15 km, azimuth 0.2 degrees. The nominal radar probability of detection is 0.8.

The scenario included a formation of closely spaced aircraft in two groups as well as other targets of opportunity. Figure 6 shows the characteristics of the formation on day one (RATT-1) and day two (RATT-2). The prescribed formation altitude was 20000 feet and the prescribed speed was 500 knots. Two additional data sets are not included here due to space limitations.

The data included primary , secondary and correlated primary-secondary reports, the latter with identification. For this assessment all reports were stripped of the identification and processed using the MHT. For this evaluation two hypotheses were retained after each scan.

The processed data for RATT-1 (5 aircraft) is presented first. Figure 7 and Figure 8 (an expansion of Figure 7) show that the processor maintains tracks even under the severe conditions presented by the data. Evaluation of the radar data shows that all five aircraft are resolved in two of the legs, whereas intra-group aircraft are mostly unresolved during the turns and two of the legs. In the centre leg only four aircraft are intermittently resolved.

Figure 9 shows the radar reports for RATT-2. The corresponding MHT tracks are shown in Figure 10. A detailed consideration of the MHT tracks was performed over the first two legs (leg one moving down from the origin and leg two subsequently moving to the right). Results indicate that all six formation flyers are accurately tracked over the first leg. During the first turn the MHT tracker loses track of the right most aircraft in each formation group (aircraft numbered 3 and 6) due to lack of measurements for these tracks over an extended number of scans. The other four tracks (inter group and intra group) are accurately maintained (with no trace of track switching) through the turn and through the second leg. Comparison of these results with the radar data reveals the robustness of the MHT tracker.

5.3 SWR Data Results

During the fall of 1993 RCL was contracted by the Canadian Department of National Defence (DND) to demonstrate IMS. Dedicated targets were made available by both the Canadian Coast Guard and the Department of Fisheries and Oceans. For the demonstration data was collected from the Cape Bonavista long range

surface wave radar system in Newfoundland, developed by RCL under contract to DND. Radar coverage is illustrated in Figure 11. The successful demonstration included detection of targets out to 200 nautical miles, tracking of highly manoeuvring targets and fusion of SWR data with ADS data.

For the trials described the radar was operated with an average power of ten watts. The radar has a range resolution of 7.5 km, and a range accuracy of 1.2 km. The azimuth resolution is 0.22 radians (12.5 degrees), and assuming a 10 dB signal to noise ratio, an azimuth accuracy of 0.5 degrees. Range rate accuracy is determined by the coherent integration period (dwell), for aircraft detection this is 10 seconds (range rate accuracy of 3.5 m/s), and for ship detection 160 seconds (range rate accuracy of 0.5 m/s). For aircraft detection the update rate is 10 seconds and for ship detection it is 300 seconds.

Figure 12 presents the best tracks propagated by the MHT for both an aircraft and a manoeuvring ship. The ship performed a figure-eight manoeuvre spanning a time duration of one hour at the point of closest approach. Twelve target updates were provided over the course of the manoeuvre. The best MHT track was maintained throughout the manoeuvre and the estimated positions showed very good correlation with ships log (on-board navigation fixes) over the entire manoeuvre. For this evaluation the MHT retained 5 hypotheses at each dwell. During the trials the average probability of false alarm (per resolution cell) was estimated to be 2e-3.

6 ACKNOWLEDGEMENTS

The Surface Wave Radar test bed, at Cape Bonavista, Newfoundland, has been developed, under contract to the Canadian Department of National Defence, by Raytheon Canada Limited.

The development of the Multisensor Multitarget processor was sponsored by the Canadian Department of National Defence through the Unsolicited Proposals Brokerage Service. Initial development of the Multiple Hypothesis Tracker was funded by Raytheon Canada Limited. The authors gratefully acknowledge the support Canadian Department of National Defence, Canadian Coast Guard and the Department of Fisheries and Oceans for providing targets and ground truth data.

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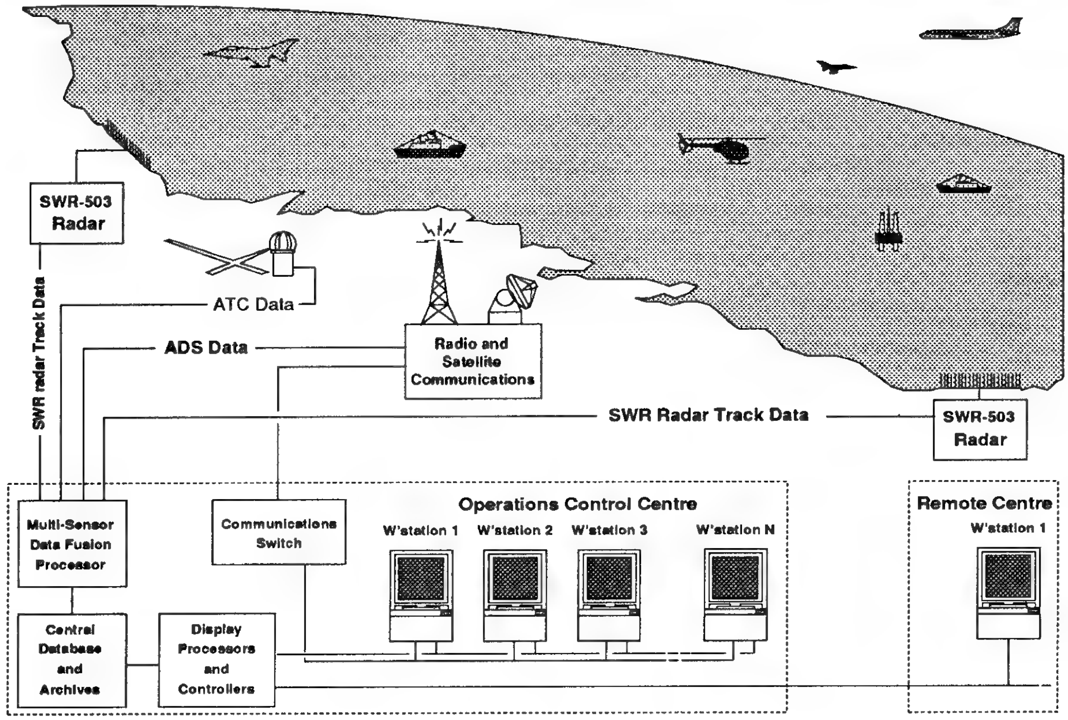

Figure 1: Integrated Maritime Surveillance System.

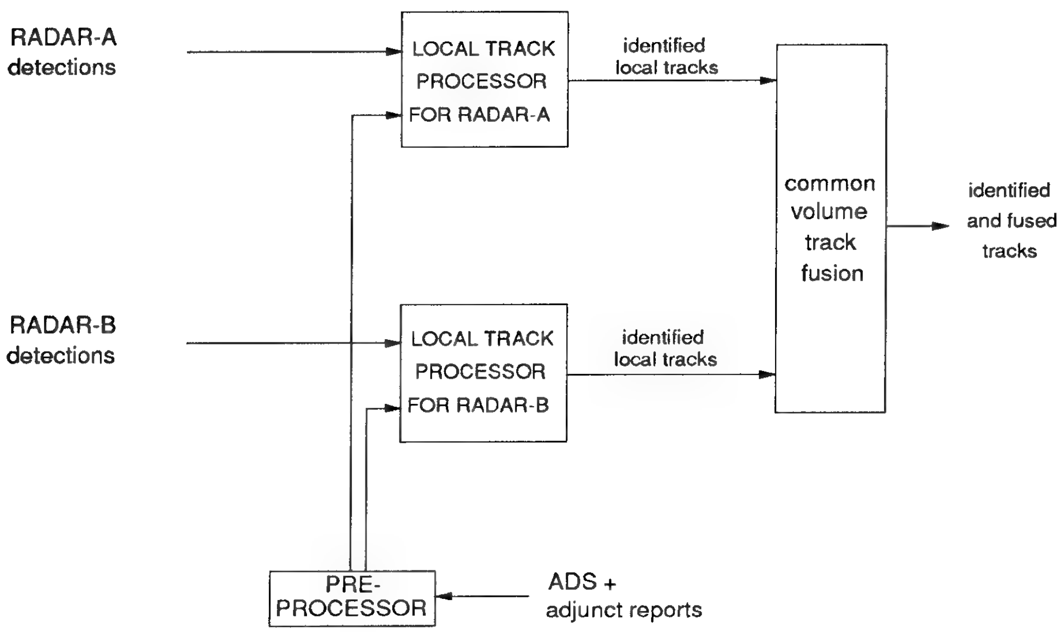

Figure 2: The overall Multisensor Multitarget Processor.

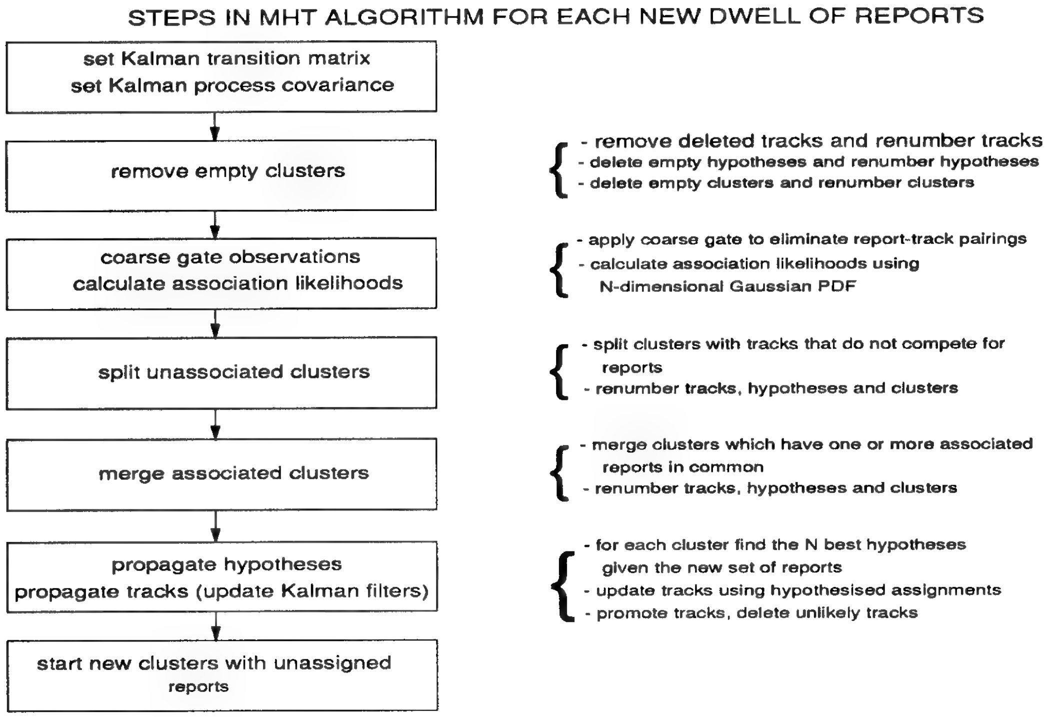

Figure 3: Processing steps for the MHT algorithm.

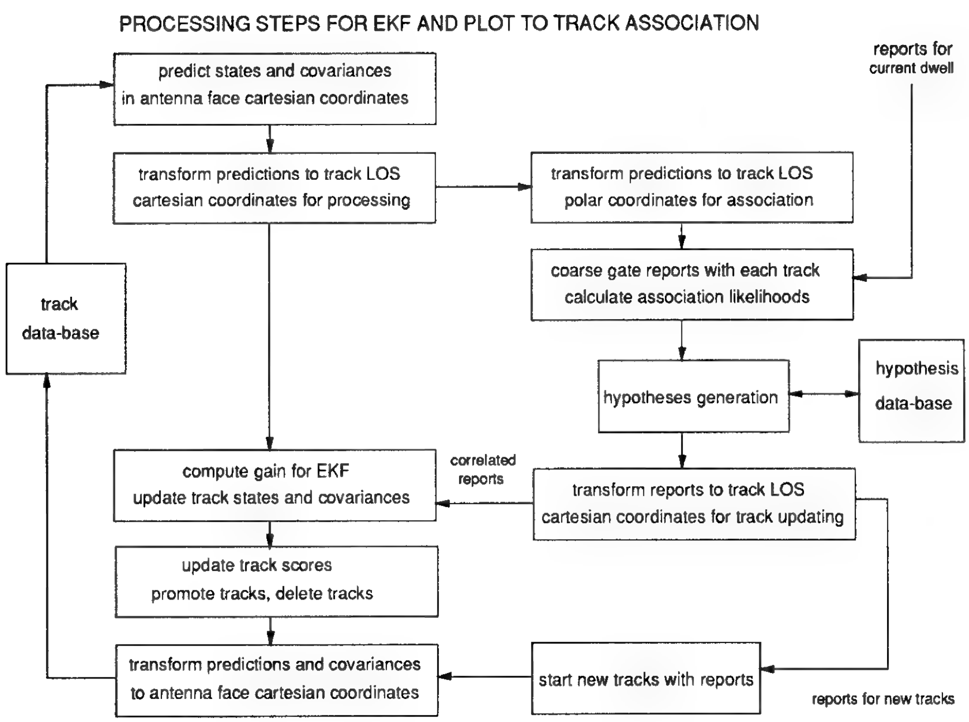

Figure 4: Kalman filter processing for coherent radar data.

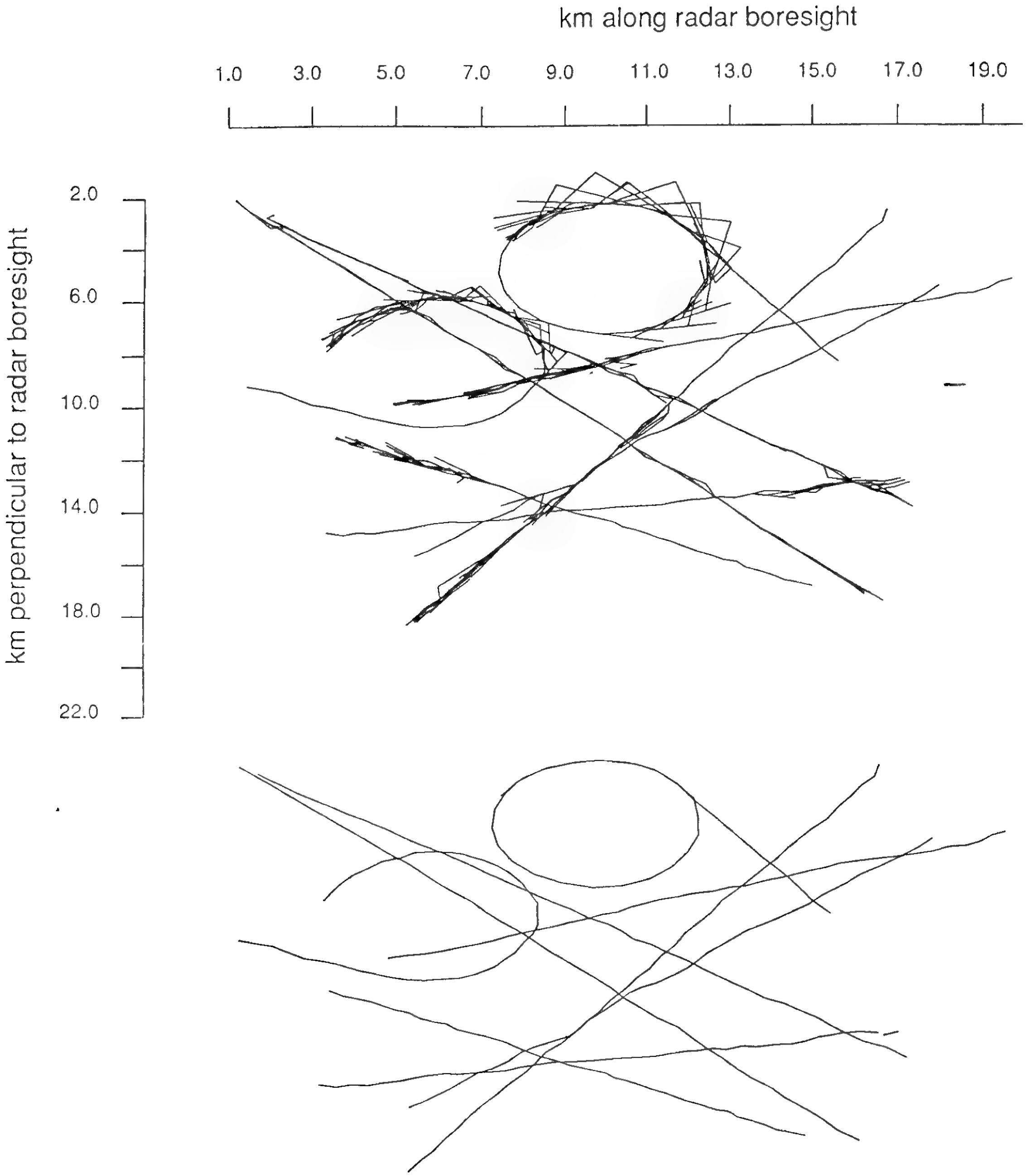

Figure 5: MHT tracks for simulated coherent radar data. Upper plot shows tracks for all hypotheses, lower plot shows tracks for best hypothesis.

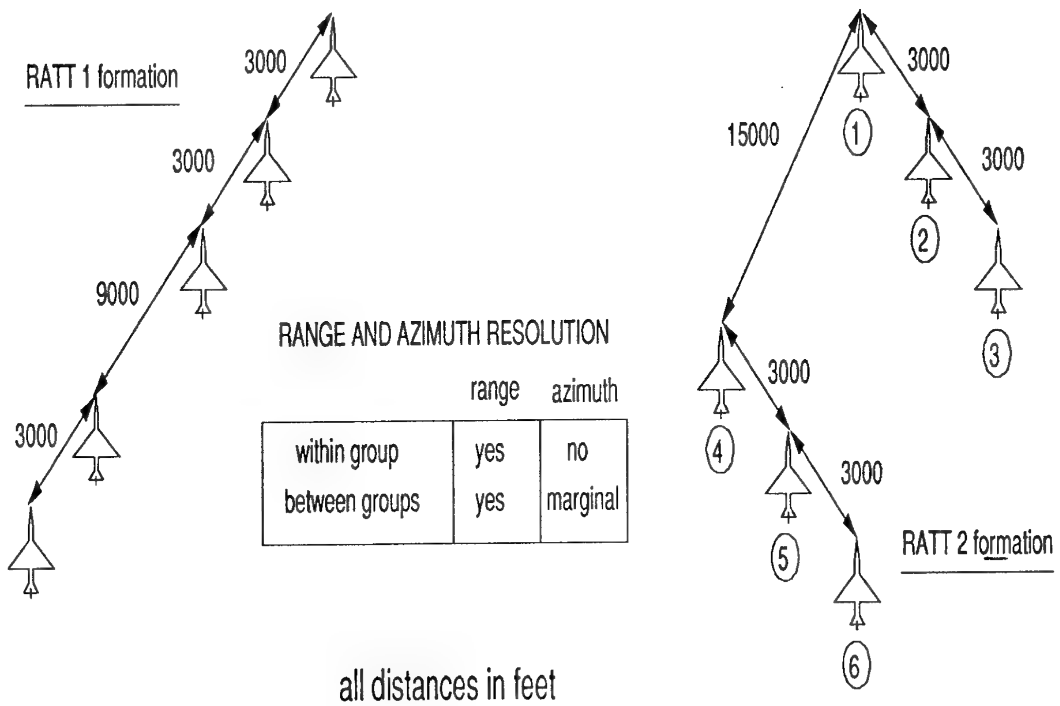

Figure 6: Prescribed aircraft formations for the non-coherent data sets used to assess MHT tracking (Raid Tracking Trials 1 and 2 respectively).

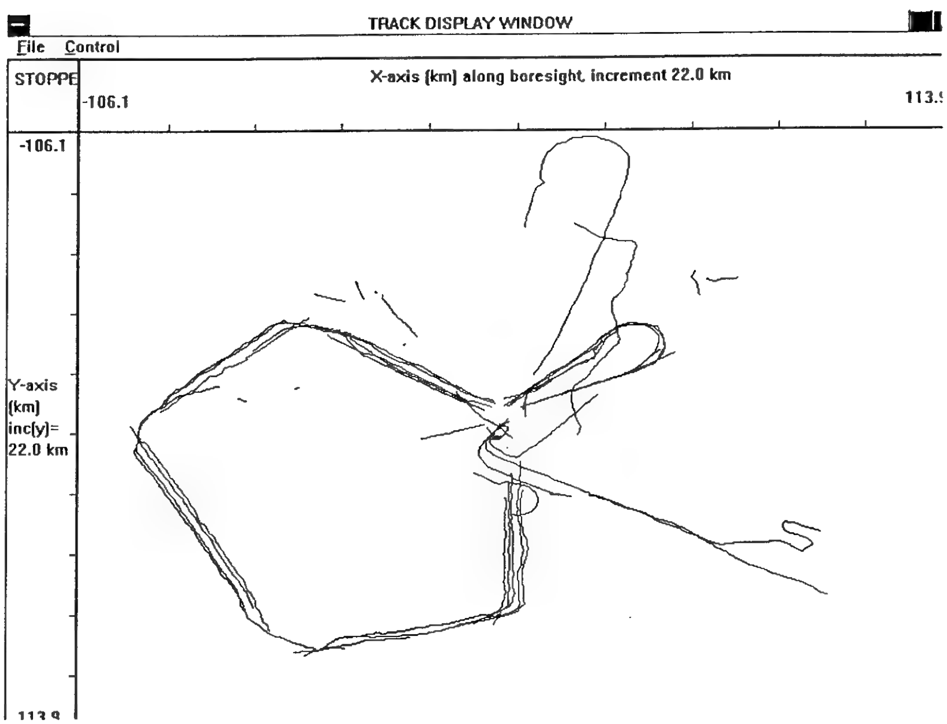

Figure 7: MHT tracks for non-coherent data set 1.

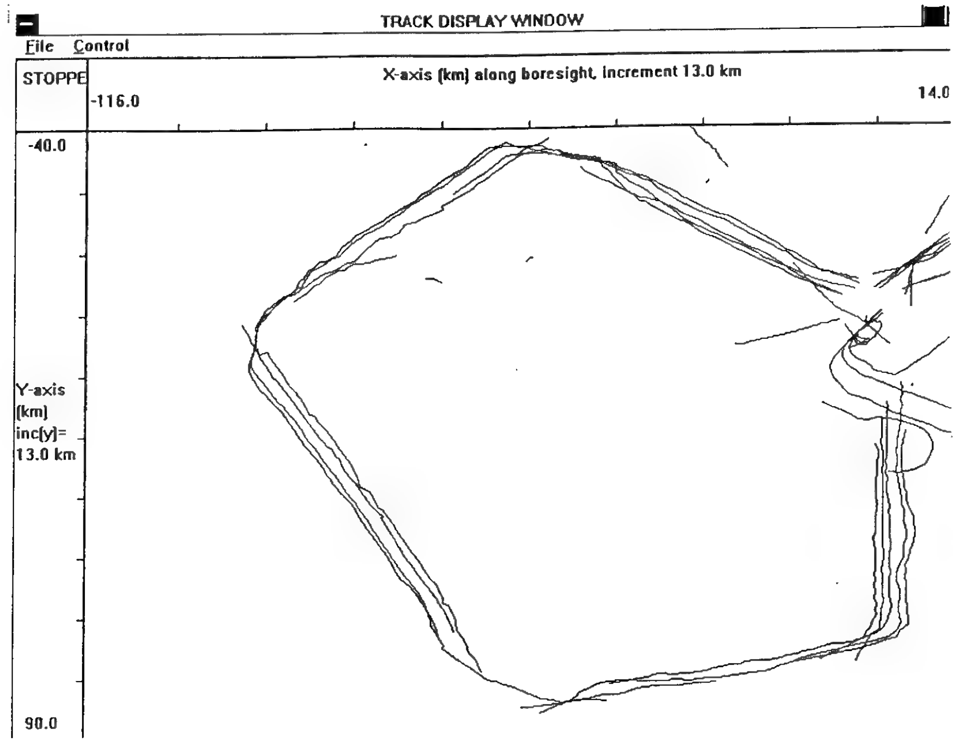

Figure 8: MHT tracks for non-coherent data set 1 (expanded view of formation tracks).

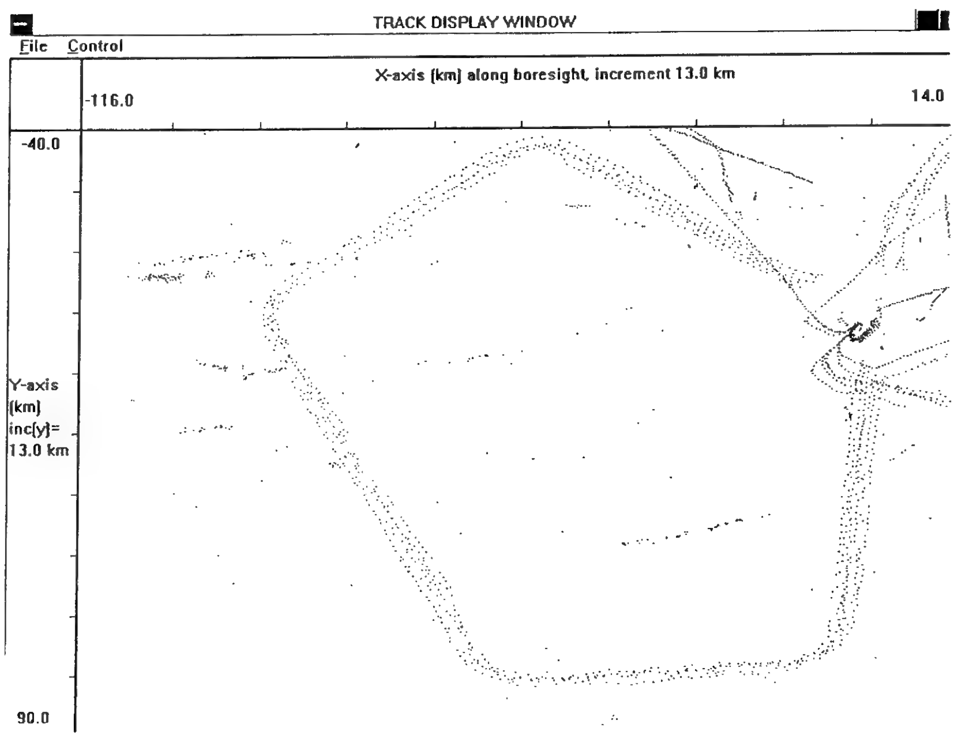

Figure 9: Non-coherent radar data set 2 showing detections for formation targets.

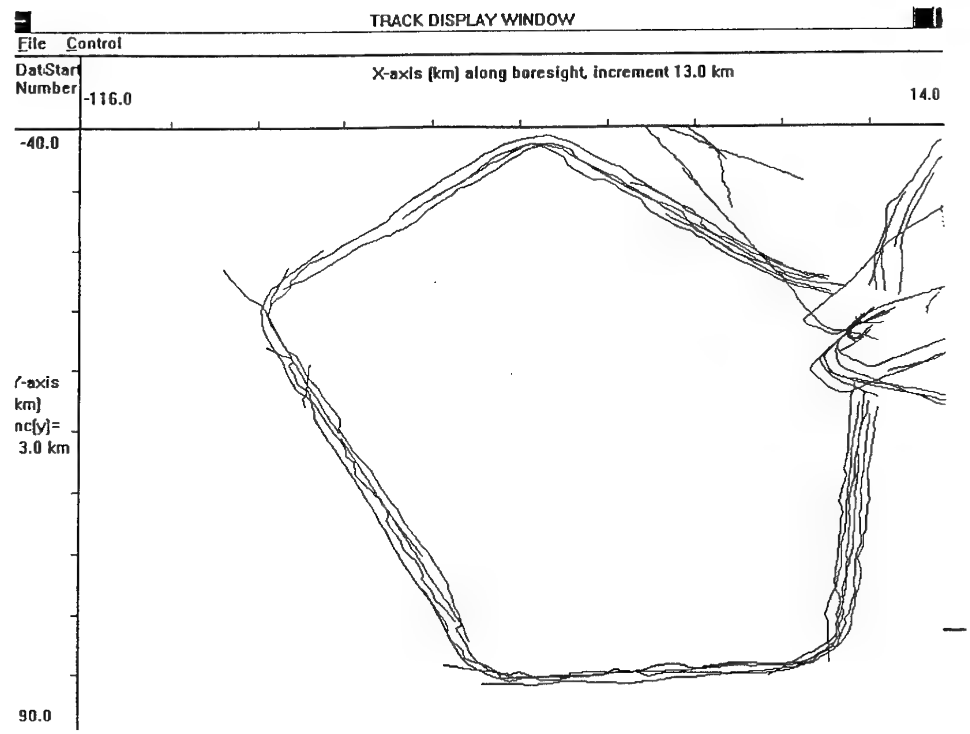

Figure 10: MHT tracks for non-coherent data set 2 (expanded view of formation tracks).

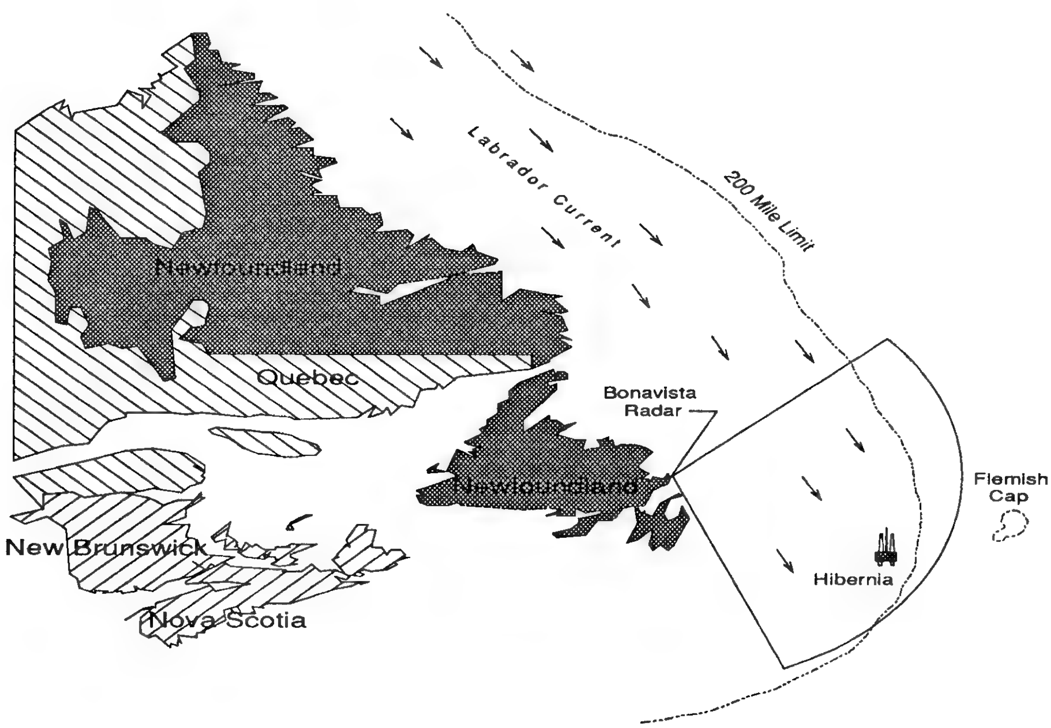

Figure 11: Surface wave radar coverage for 1993 Cape Bonavista trials.

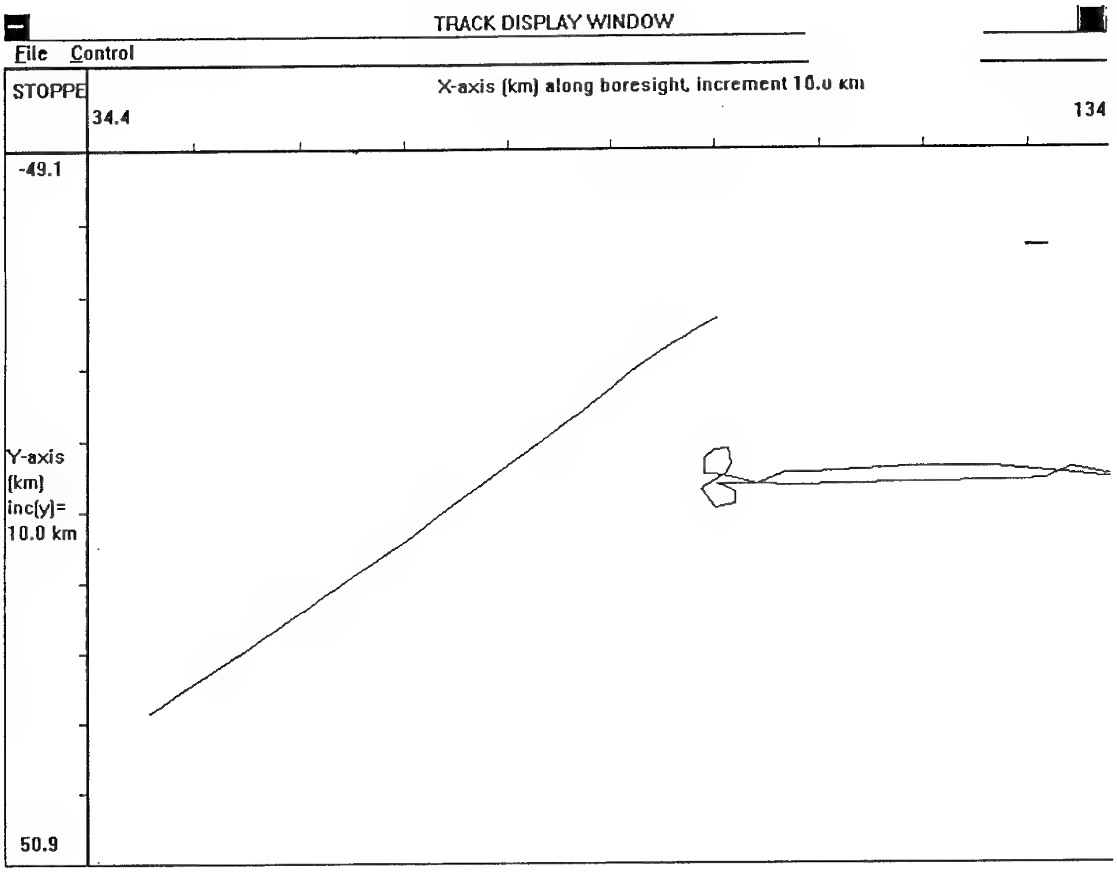

Figure 12: MHT tracks for manoeuvring ship and aircraft detected during Cape Bonavista trials.

Multiple Target Tracking Based on Constellation Matching and Kalman Filter

Andrew K. C. Wong

PAMI Laboratory
Department of System Design
University of Waterloo
Waterloo, Ontario, Canada
N2l 3G1

Henry Leung

Surface Radar Section
Radar and Space Division
Defence Research Establishment Ottawa
Ottawa, Ontario, Canada
K1A 0K2

Abstract

A new approach to multiple target tracking (MTT) problem is developed. The data association (DA) problem is solved by an attributed subgraph isomorphism approach called constellation matching (CM). The CM method exploits, in the most direct way, the spatial configuration of the collection of targets which are subject to temporal and spatial constraints. The CM-based tracking system combines the CM technique with the Kalman filter to track and confirm the trajectories of multiple targets. The efficiency of this new approach is demonstrated using real-life multiple target radar tracking data and the results are compared to those obtained by a multiple hypothesis tracking (MHT) system.

1. Introduction

Multiple target tracking (MTT) [1] addresses the issues of using one or more sensors to simultaneously track many moving objects of interest (targets). It is an essential requirement for surveillance systems to interpret an environment that includes both true targets and false alarms. The objective of MTT is to partition the sensor data into sets of observations, or tracks, originated from the same source. Once tracks are formed and confirmed, a number of quantities, such as number of targets, target kinematics and other characteristic parameters, can be estimated and predicted.

For single target tracking, a sequence of target positions can be detected from sensed data referred to as plots which can be plotted to give a trajectory of the target. The detected trajectory up to the current frame can be used to predict the position of the target using standard Kalman filter in the next frame. However, for a MTT system, the problem is more complicated. A major difficulty in tracking a large number of moving targets is the uncertainty in the origin of measurements; that is, in general it is not known what the correct association is between measurements and targets. For example, in the case of a single sensor producing noisy measurement of the ranges of N targets, there are a total of $N!$ possible associations between the measurements and the targets. Thus even for a relatively small number of targets, the number of possible target/measurement associations can be very large. The standard approaches to MTT are based on some subset of the set of all possible associations which can result in computationally complex algorithms in the application to collections of many targets in the

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

same validation gate.

In this paper, a novel method called constellation matching (CM) [2] is proposed to solve this assignment problem. The CM-based MTT system consists of two major components: association and prediction. Because Kalman filtering is sequential and optimal in the minimum mean-square sense, it is used in our MTT system to perform the prediction. As for association, this new MTT system uses the CM technique to perform observation-to-track assignment. The CM method forms a complete graph on the tracks and matches it to graphs formed by the measurements received in the next scan to minimize possible errors arising from local target positional variation or false alarms due to the presence of noise. Our MTT system then combines the CM technique with the Kalman filter to track and confirm the trajectories of multiple targets.

In Section 2, the constellation matching technique and its application to the association problem is described. In Section 3, we present the algorithm of the CM-based MTT system. Evaluation of this new MTT system using real-life radar tracking data and the comparison with a multiple hypothesis tracking (MHT) algorithm are reported in Section 4.

2. Data Association and Constellation Matching

Data association (DA) is the process of assigning observations to existing tracks. It is of fundamental importance to a MTT system. For closely spaced targets, it is likely that conflicting situations may arise in the following cases: 1) when multiple observations fall within the same gate; 2) observations fall within the gate of more than one track. In general, there are two approaches to the DA problem. One is a deterministic approach which includes nearest neighbor (NN) and global nearest neighbor (GNN) data association. The other one is the probabilistic approach based on Bayesian framework, which includes multiple hypothesis tracking (MHT), probabilistic data association (PDA) and joint probabilistic data association (JPDA).

In this paper, a novel method called constellation matching (CM) [2] is proposed for data association. Basically, the CM method is a special case of a more general methodology known as optimal attributed subgraph isomorphism [3,4], where the optimal DA is achieved by assigning observations to tracks in order to minimize a chosen objective function. In the CM method, the objective function takes into the consideration the preservation of spatial configuration of associated points between consecutive frames. The CM method is deterministic; it is, however, more general than the NN approach since it tries to preserve maximal spatial correspondence between configurations of data points in two consecutive frames. It is also similar to the MHT in the sense that it generates possible data correspondence between two consecutive frames. However, the CM method chooses the best solution for the two consecutive scans while the MHT generates a number of candidate hypotheses and uses new

data to select the best track. The general principles of CM-based DA is described in the following.

Consider a group of *N* targets { T_i, i = 1, ..., *N* } represented by an attributed graph *G* in which each target T_i is represented by a vertex v_i and $d(T_i, T_j)$, the distance between T_i and T_j, is the attribute value assigned to the edge (v_i, v_j). The attribute graph *G* so defined is referred to as a constellation.

Let *G1* and *G2* be the constellation in two consecutive frames respectively. Association between targets in different frames can be realized by establishing an optimal one-to-one mapping *f* between the vertices in *G1* and *G2* while optimizing a certain objective function *F*. *F* is defined as:

$$F(G1,G2) = \sum_{\forall v_i, v_j \in G1, i \neq j} C(v_i, v_j) \qquad \textbf{(1)}$$

where

$$C(v_i,v_j) = \begin{cases} 0 & If\, any\, one\, of\, v_i, v_j, f(v_i), f(v_j)\, is\, null \\ |d(v_i,v_j) - d(f(v_i),f(v_j))| & otherwise \end{cases} \qquad \textbf{(2)}$$

The CM technique is then the problem of choosing *f* that achieves optimal target matching which minimizes *F*, and we denote such an optimal mapping by *f"*.

The CM-based DA technique can be summarized as follows:

1. For each pair v_i and v_j in *G1*, compute $d(v_i, v_j)$;
2. For each pair u_i and u_j in *G2*, compute $d(u_i, u_j)$;
3. Find all possible mapping; that is, find a set of points u_1', u_2', ..., u_N' in *G2* where u_i' can be a null vertex (one that assumes a null value but can still be matched to a v_i in *G1*) or an actual vertex in *G2* so that u_i' is matched to v_i in *G1*;
4. For each feasible mapping, compute the value of the objective function *F*;
5. Choose the mapping *f"* that minimizes *F*.

When the number of targets is large, a combinatorial explosion may happen in the CM method, either in computation time or in storage space. Heuristics which exploit spatial/ geometric constraints of the constellation are introduced to reduce the computational complexity. The following are some of the spatial and temporal constraints we adopt:

1. One basic assumption of a MTT system is that the distance a target can reach within the time interval between consecutive frames which cannot exceed a predefined maximum value (i.e. the maximum distance the target can travel within that interval). Thus, a pre-specified maximum size of the predicted region is imposed while finding the possible matches between vertices in *G1* and *G2*. This spatial constraint is particularly useful in the track initiation stage because there are not enough plots to render meaningful prediction.
2. Another assumption is that the distortion of a constellation cannot exceed a certain value, i.e. $C(v_i, v_j)$ cannot exceed a predefined maximum value. Hence, a pre-specified tolerance of the change is distance between two consecutive frames is introduced in our CM system to eliminate the infeasible matches.

3. When there are too many vertices in *G1*

needed to match with vertices in *G2*, a space partitioning method using the maximum entropy method [5] can be introduced to partition *G1* into several subgraphs (or sub-constellations), each of which would contain say 5 to 10 vertices. Thus the solution space for CM is drastically reduced. This makes the CM method feasible and effective for scenarios with large number of plots.

To illustrate the idea of using CM for DA, an example using the real-life radar tracking data is shown in figures 1 to 4. Data are extracted from five consecutive frames. *A*,s are used to denote plots received in scan number 1, 3 and 5, and *B*,s are used to represent those in scan 2 and 4. For figures 2 to 4, numbers of plots are the same for the two consecutive frames, and we observe that the CM produces correct associations for four scans. In figure 1, there is an extra plot in the first scan, however, the CM method can still perform a correct graph matching between the two frames of data.

3. A Constellation Matching Based MTT System

The CM-based MTT system proposed in this paper consists of five major components:

1. Data pre-processing

The measured kinematic quantities of data points may not be in the suitable form for performing MTT function. Hence, the first step in our MTT system is data pre-processing which transform the original data format received by the radar to a suitable one to be used for subsequent analysis. In this study, the radar data is transformed from polar to Cartesian coordinates.

2. Gating and clustering

The purpose of this step is to classify an observation into one of the two categories: isolated observation and closely spaced observation. Clustering is used to form constellations for the future target association. Gating is used to partition the measurements in the next frame into two categories: i) candidates within the connected neighborhoods (or gates) of points in the previous frames, and ii) data points that can be considered for new tentative track initiation. Figure 5 illustrates the application of gating to four new observations based on the gates of two points in the previous frame. In figure 5, *P1* and *P2* are the tracks. Let *O1, O2, O3* and *O4* be four observations in the current frame. *Gate1* and *Gate2* are the circular gates of *P1* and *P2* respectively with the maximum estimated target displacement between consecutive time frames as their respective radius. Here, *O1, O2* and *O3* are within *Gate2* whereas *O1* is also within *Gate1*. Hence, *O1, O2* and *O3* can all be considered to be associated with *P2* whereas *O1* can be considered as associated with either *P1* or *P2*. These three observations belong to the first category. *O4* is outside of both gates and hence cannot be associated with either *P1* and *P2*. Hence, *O4* belongs to the second category.

3. Data association using CM

CM method is used to obtain the correspondence between the observations in the last frame and those in the new frame as described in the previous section.

4. Track formation

In this step, each assigned observation is put into its corresponding track which records the trajectory of the associated target. The maximum size of the predicted region is used as the radius of the circular gate for the measurement association. There are two possible situations: isolated observations and closely spaced observations. Once a new scan of measurement is received, three cases may arise for an isolated observation:

i) If there is no measurement in its association gate, the region is enlarged to the pre-specified size. If there is still none, then no assignment can be made to that isolated observation.

ii) If only one observation is found in its association gate, then it is assigned to the proceeding isolated observation.

iii)If more than one observation is found in its association gate, then use the prediction to choose the most suitable observation for the assignment.

Closely spaced targets are those whose predicted regions overlap with others. We group these observations to form a cluster, and these observations together become the vertices of *G1*. In the new frame, choose those observations that lie within the combined region (or cluster) to form another constellation *G2*. Then apply CM to find the target association between *G1* and *G2*.

5. Trajectory prediction

In the CM-based MTT system, a Kalman filter given as

$$\begin{aligned} \mathbf{x}(k) &= (x(k), y(k))^T \\ \hat{\mathbf{x}}(k+1) &= \Phi\hat{\mathbf{x}}(k) + K(k)[m(k) - H\hat{\mathbf{x}}(k)] \\ K(k) &= \Phi P(k) H^T [H P(k) H^T + R(k)]^{-1} \\ P(k+1) &= [\Phi - K(k)H] P(k) \Phi^T + Q(k) \end{aligned} \qquad (3)$$

where $\mathbf{x}(k)$ = ($x(k)$, $y(k)$) is the kth time point of the specific target, is used for trajectory prediction to provide predicted gating to reduce the number of measurements for data association.

4. Real Data Analysis and Comparison with the MHT

In September 1986, under the auspices of the Technical Cooperation Program, Canada and United States established a data base of raw radar data on formations of closely spaced military aircraft to support research and development on multiple target tracking. The experiment took place at Canadian Forces Base, Cold Lake, Alberta. Six CF-18 fighter aircraft, flying prescribed routes in prescribed formations, served as "raid" targets. Formations of CF-18 fighter were flown in two missions, each consisting of two tests. For the first mission, a formation of three aircrafts and a formation of two aircrafts were used; for the second mission, two formations of three aircrafts were used. The layouts of the two formations are shown in figure 6. For each test, the spacings between aircrafts in the group and between groups were varied. In both tests, the aircraft flew the same prescribed routes. Flying time per test was about one half hour.

Only four types of data were kept for the database: primary radar detections (ASR),

secondary radar detections (SSR), correlated detections from primary and secondary radars (SSRC) and time marks (TIME). There are four data sets designated as R1T1.dat, R1T2.dat, R2T1.dat and R2T2.dat. Table 1 reports the statistics of the experimental results of the CM-based MTT system. The first row tabulates the total number of CMs conducted between consecutive frames. The second row reports the number of CMs that yield correct data association out of the total number tabulated in the first row. The third row reports the number of CMs which do not yield completely correct data association due to abrupt change of the trajectory. The fourth row reports the number of CMs which do not yield completely correct data association due to the presence of noise. The fifth row reports the number of CMs which do not yield completely correct data association due to the missing information in the plots.

In order to understand the CM-based tracking technique further, various experiments are conducted. First, we remove all the plots without target ID to make it easier to evaluate the tracking performance. Since it is impossible to show the complete result of the CM for all frames in detail (there are totally around 180 frames), we show part of the matching results in Figure 7. In order to get detailed information on the change of formation of this constellation we also plot a sequence of time frames in Figure 8 where the tracks start from the lower right corner of the figure.

Next we use the ASR data to analyze the performance of the CM method. There are usually five or six targets in a data set, but only two of them are given ID. To test the correctness of CM, we could only use targets with known ID's for confirmation; i.e., during each step of target association, we match all the observations (both ASR and SSR) between the two consecutive frames. But for testing, we are only able to determine if the matches are correct for the SSR data. If a target in the previous frame is associated with the target in the succeeding frame with the same ID, we consider it a correct match. Part of the global results for one CM is shown in Figure 9. Also, a sequence of time frames starting from the lower right corner are plotted in Figure 10 to illustrate the matching results. Figure 11 and 12 show the global results for two typical targets in R1T1.dat (with ID numbers of 130 and 205 respectively).

To compare the efficiency of the CM-based MTT technique with conventional methods, a multiple hypotheses tracking (MHT) [7] algorithm is implemented and applied to the same real data sets for comparison. The main idea of MHT is that if a difficult association decision arises when a new scan of plots is received, MHT attempts to defer the decision by assigning all reasonably likely association as hypotheses. Each hypothesis is then given a probability given as

$$\begin{aligned} P_i(k) = {} & \frac{1}{c} P_D^{Nc} (1 - P_D)^{Nt-Nc} \beta_{ft}^{Nf} \beta_{kt}^{Nn} \\ & \left[\prod_{j=1}^{Nc} N(y_k - H\hat{x}, B) \right] P_i(k-1) \end{aligned} \qquad \mathbf{(4)}$$

where P_D, β_{ft}, β_{kt} are the probability of detection, the density of the false targets, and the density of

new targets, respectively. c is a normalization constant and $P'(k\text{-}1)$ is the probability of the hypothesis $L_i(k\text{-}1)$. $N(x,B)$ denotes the normal distribution and $B = HP_cH' + R$ where P_c is the covariance of a target estimate for the prior hypothesis $L_i(k\text{-}1)$ and R is the measurement noise covariance. It is anticipated that incorrect hypotheses will lead to highly unlikely cumulative probabilities, and hence only the most likely hypothesis will be found at the end.

Although the MHT is theoretically sound, its major handicap is the high computation cost due to the exponentially growing hypothesis tree. The situation becomes worse when the number of targets or clutter are large. In order to limit the growth of the hypothesis tree, four auxiliary techniques used in the CM-based MTT method are also introduced in the MHT algorithm so that we can have a fair comparison.

1. Gating: the same gating used in the CM-based MTT method is used here. In other words, those plots that fall outside of the gate are not used for potential hypotheses of the target.
2. Pruning: hypotheses with low probability are eliminated to keep a manageable hypothesis tree. In our implementation, we limit the number of new tracks generated to a maximum of three.
3. Merging: those tracks or hypotheses whose effects are similar (say with the same value within the newest frames) are merged to form a new track or hypothesis.
4. Clustering: those hypotheses which interact with each other are combined into one cluster.

The flow chart of our MHT implementation is given in Fig.13.

The same four data sets are applied to both MTT systems and the statistical results are listed in Table 2. The statistical results are made using same targets along same time frames. From Table 2, the CM method appears to have a better performance than the MHT for these four real data sets. Figure 14 shows an example of the comparison between the tracking of the same target using the CM method and the MHT, and the improvements of the CM method are highlighted.

5. Discussion and Conclusion

In this paper, a new multiple target tracking system based on the constellation matching technique is introduced. Preliminary experimental results using real-life radar tracking data indicate that the CM-based MTT system is efficient in the sense that it produces over 80% of correct target associations. It fails only when the aircraft performs high maneuvering turns and missed detections occur. Comparing with the MHT, the CM-based MTT shows improvement in the computational cost and tracking accuracy due to the effective use of spatial constraints.

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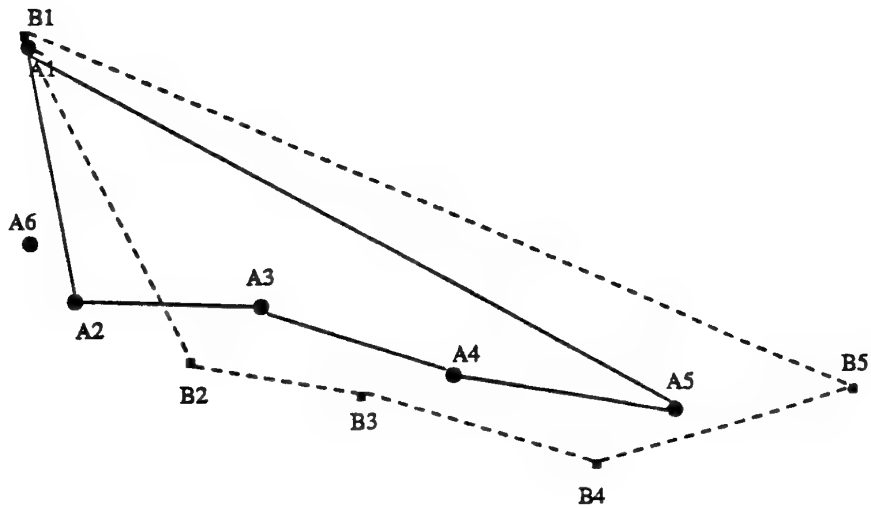


Figure 1 Pairly Constellation Matching Result 1

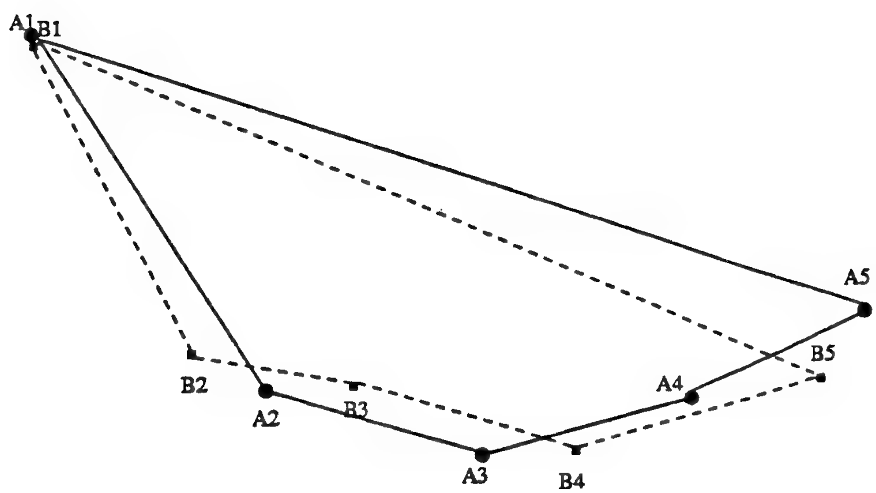


Figure 2 Pairly Constellation Matching Result 2

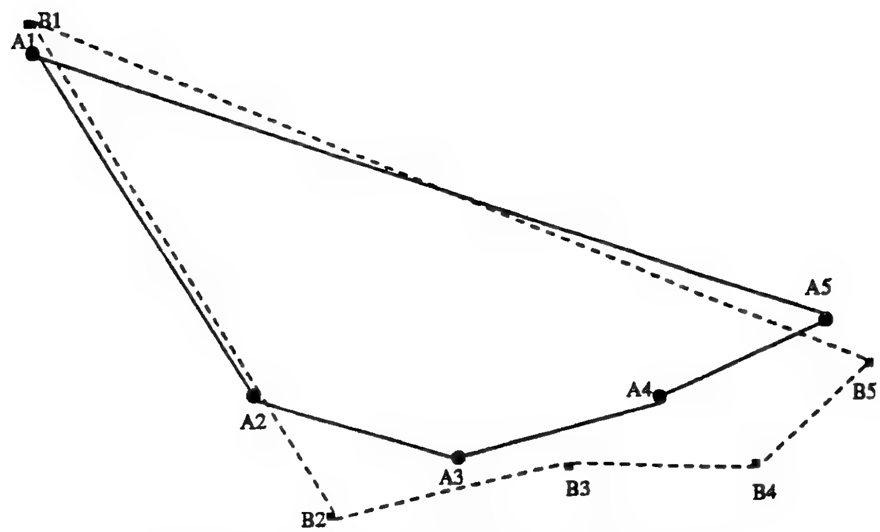


Figure 3 Pairly Constellation Matching Result 3

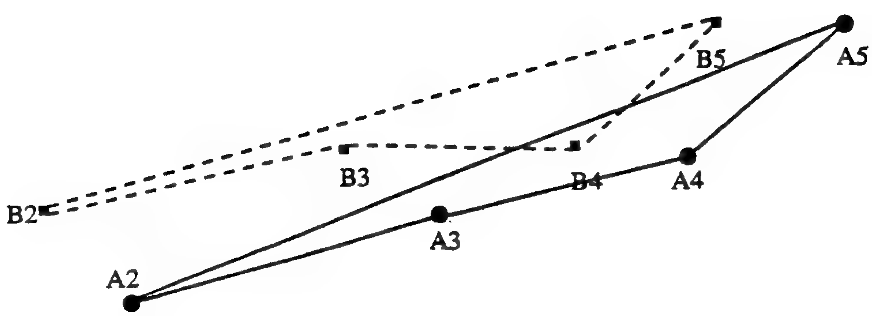


Figure 4 Pairly Constellation Matching Result 4

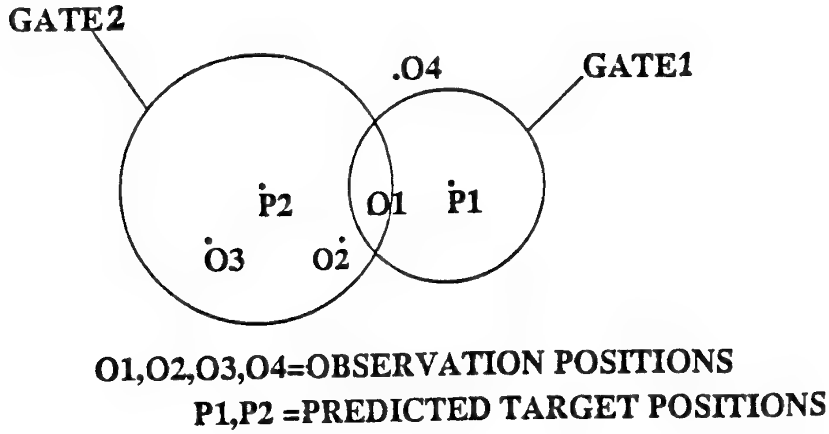
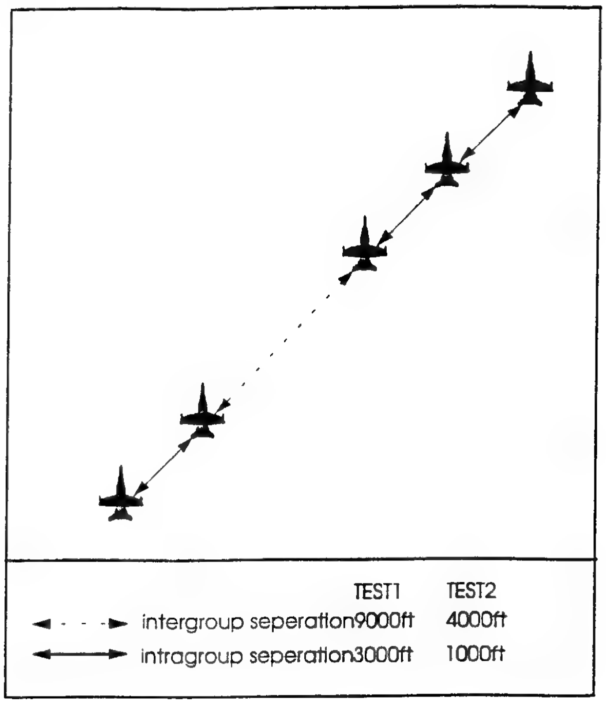


Figure 5 Gating and Correlation for Two Closely Spaced Tracks



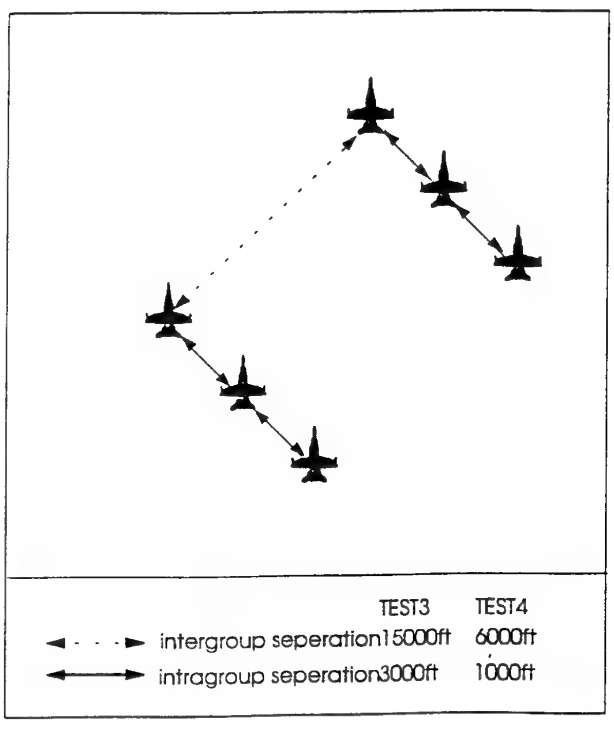


Figure 6 Formation Layout for Mission 1 and 2

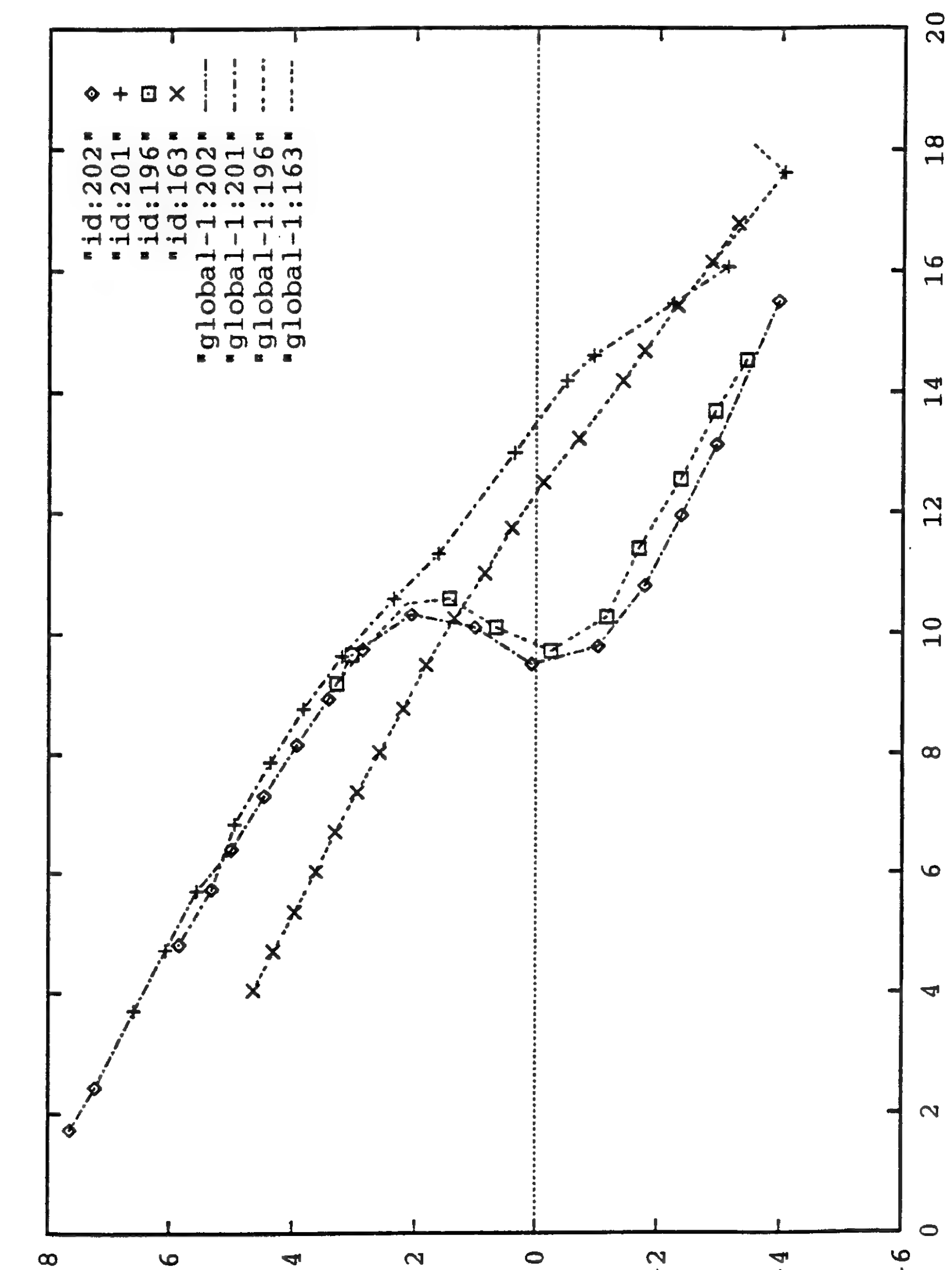


Figure 7 Part of Global Tracking Result of One Constellation (Only for SSR)

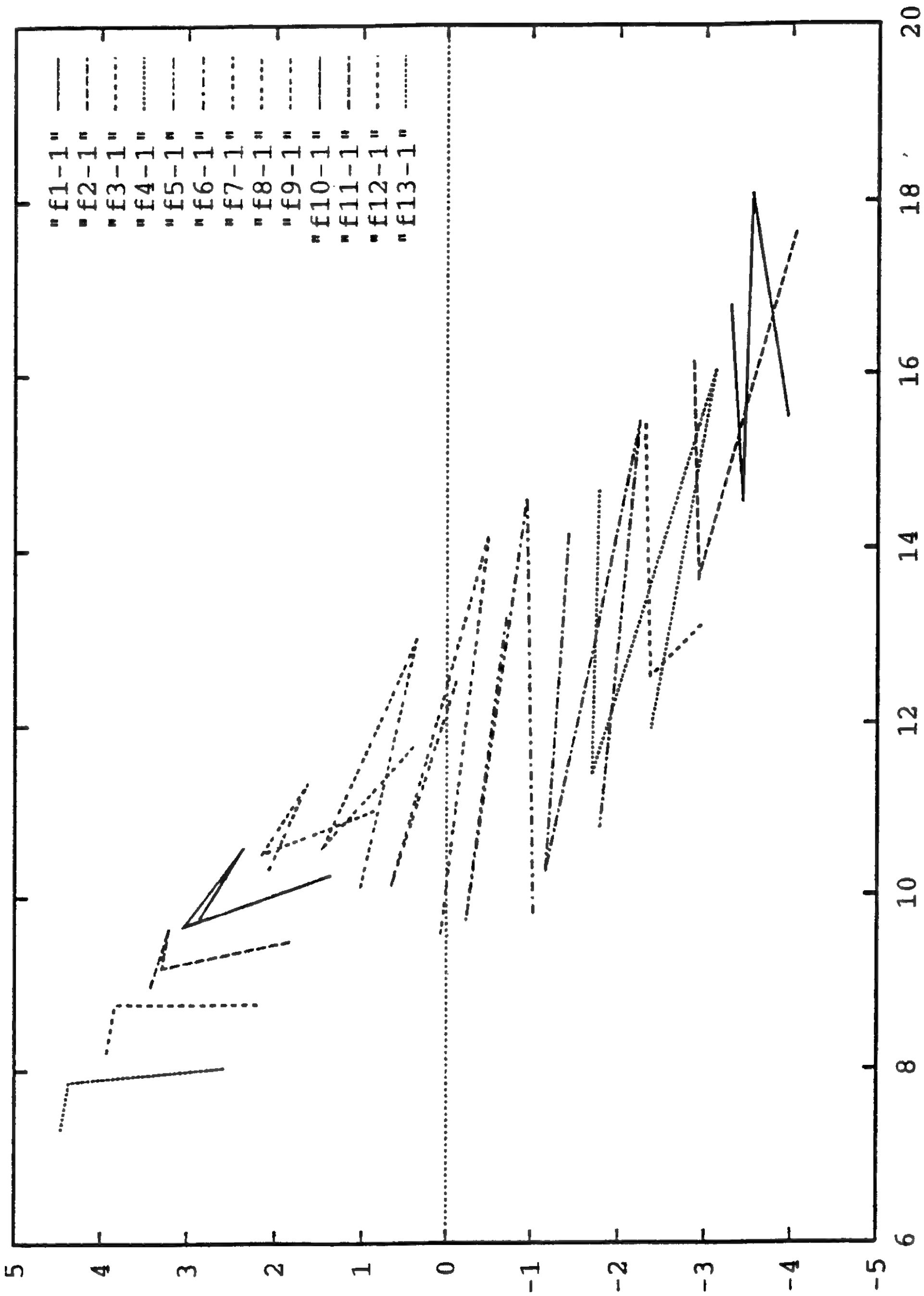


Figure 8 Part of a Sequence of Time-frames for One Constellation (Only for SSR)

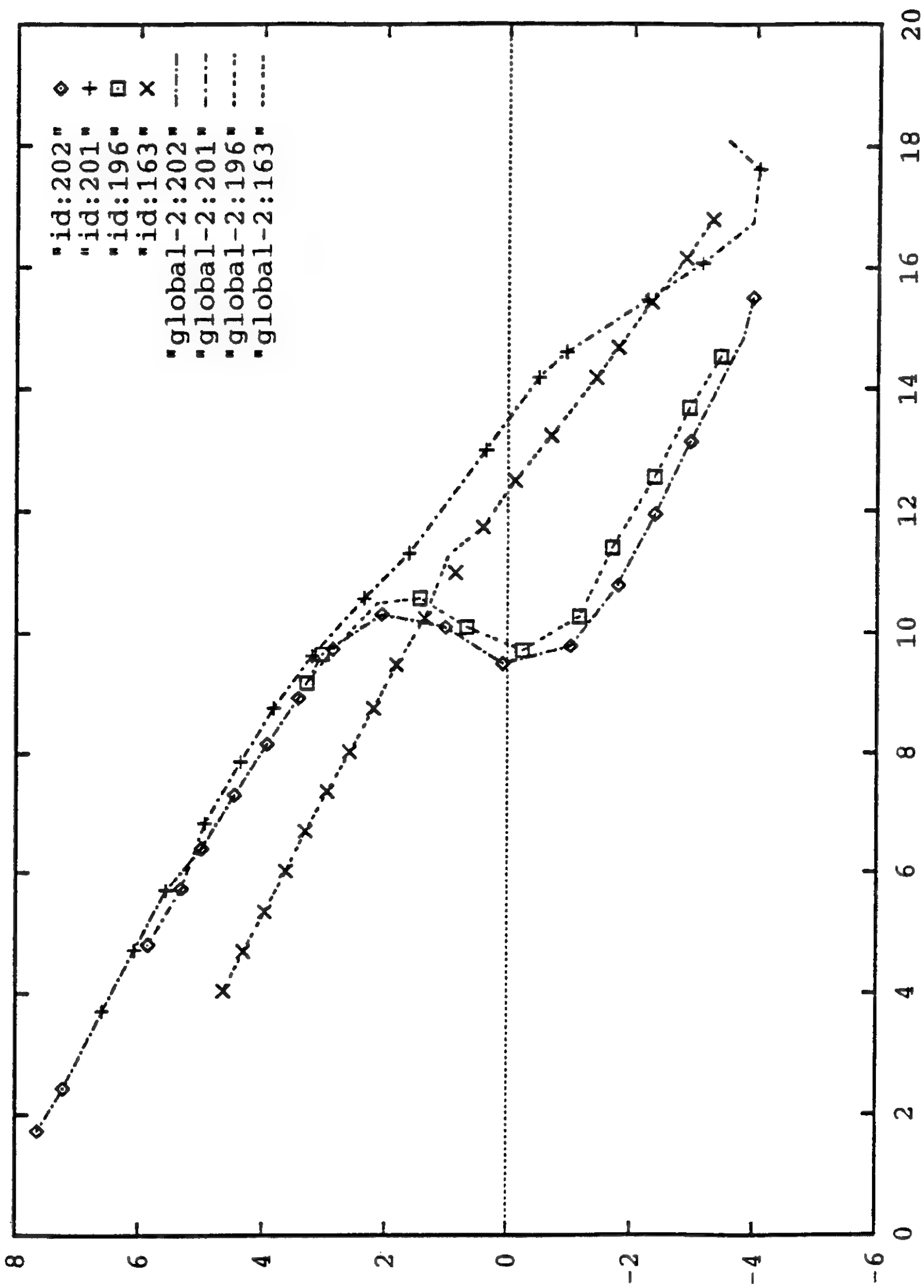


Figure 9 Part of Global Tracking Result of One Constellation (Both ASR and SSR)

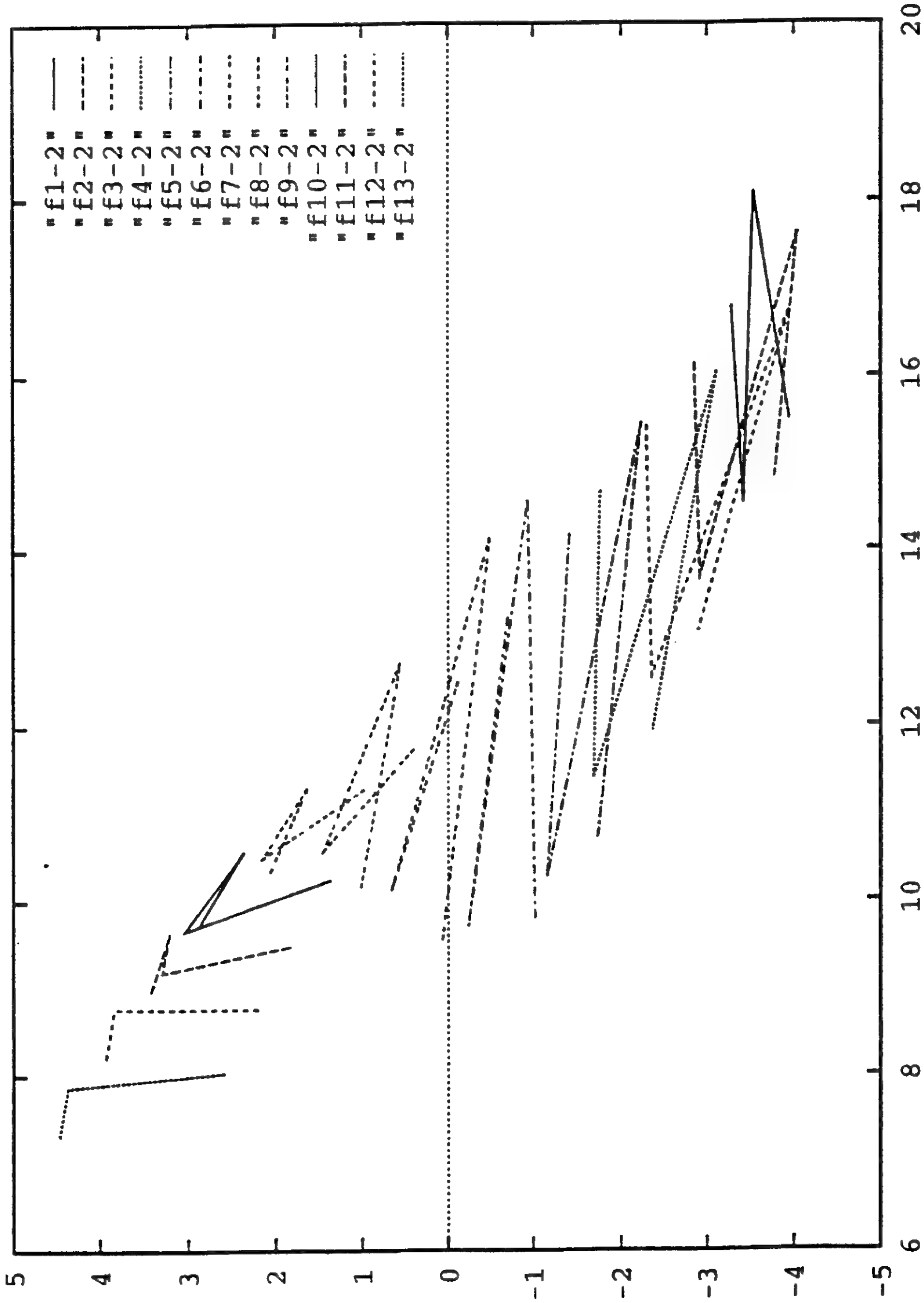


Figure 10 Part of a Sequence of Time-frames for One Constellation (Both ASR and SSR)

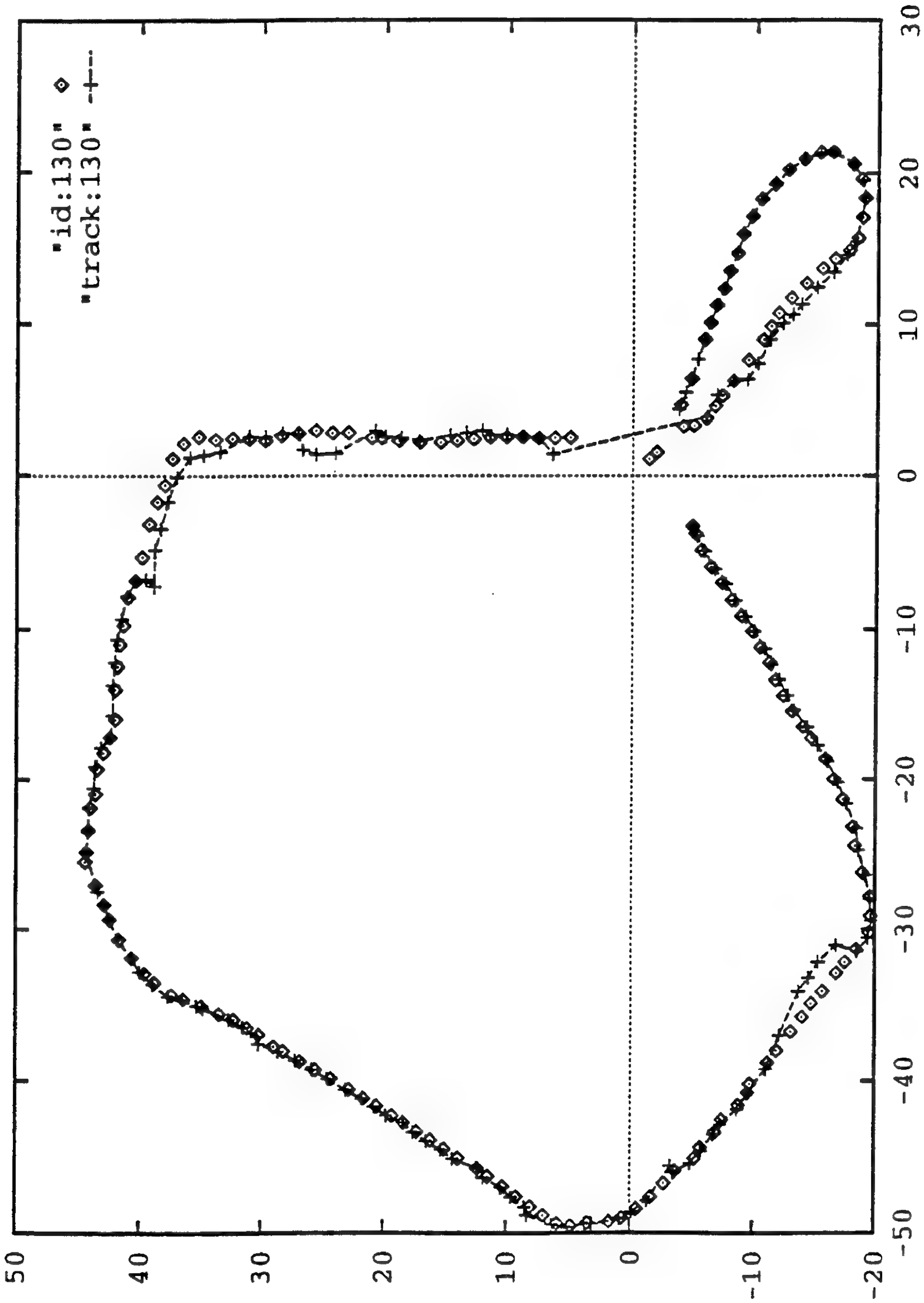


Figure 11 Global Tracking Results of One Target in R1T1.DAT (ID 130)

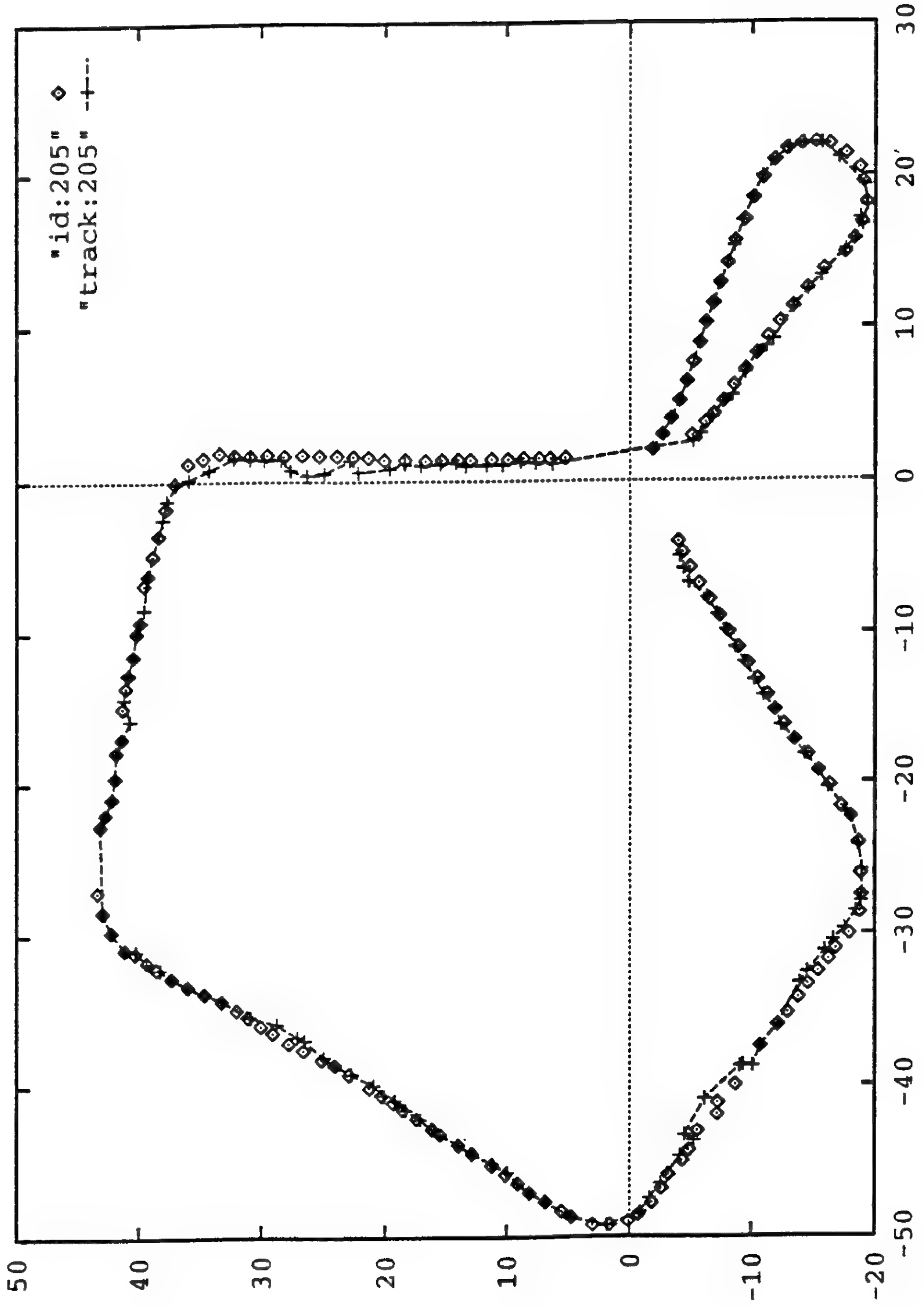


Figure 12 Global Tracking Results of One Target in R1T1.DAT (ID 205)

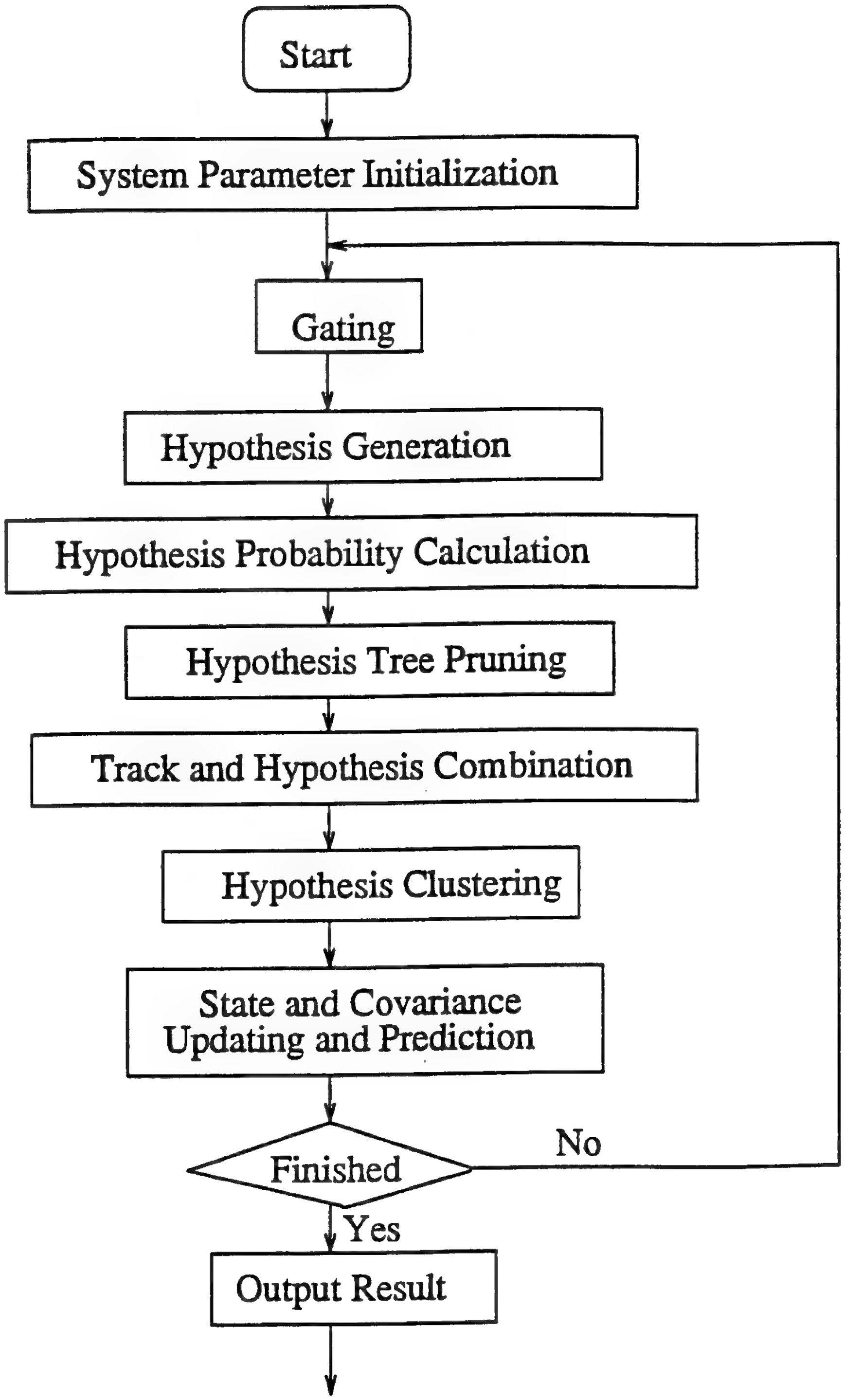


Figure 13 Multiple Hypothesis Tracking Flow Chart

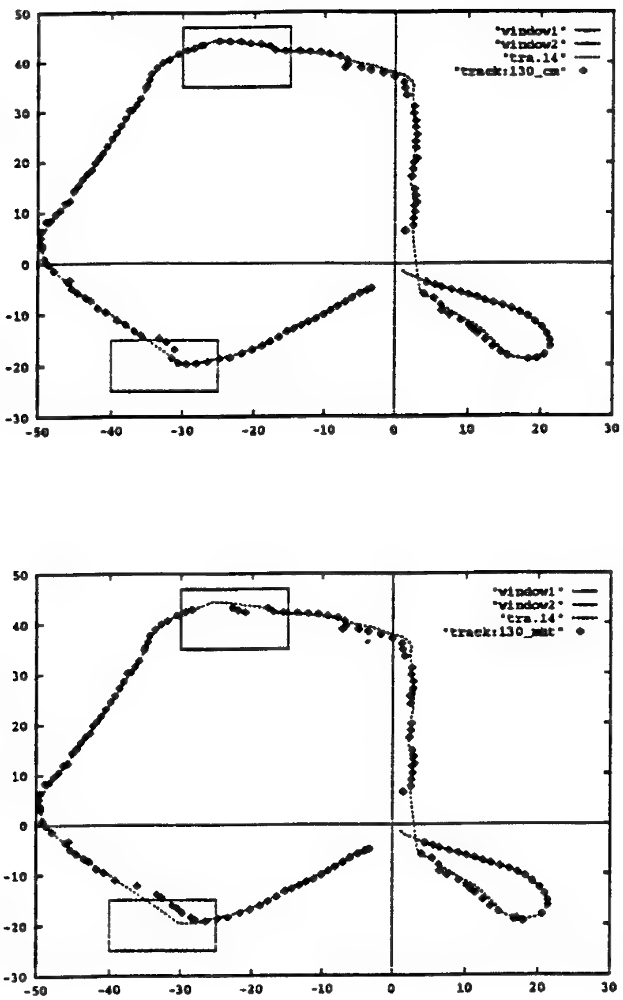


Figure 14 Comparison between the CM Method and the MHT

	R1T1	R1T2	R2T1	R2T2
No. of Occurance of Constellation Matching	172	177	187	168
No. of Correct Constellation Matching	145	143	147	137
No of Wrong Constellation Matching due to Sudden change	16	21	29	19
No of Wrong Constellation Matching due to Noise	8	5	3	8
No of Wrong Constellation Matching due to Info. Lose	3	8	6	4

Table 1 Result of the CM-based MTT System

R1T1.DAT

	Total	Correct	Wrong
CM	172	145	27
MHT	172	130	42

R1T2.DAT

	Total	Correct	Wrong
CM	177	143	34
MHT	177	127	50

R2T1.DAT

	Total	Correct	Wrong
CM	187	147	40
MHT	187	116	71

R2T2.DAT

	Total	Correct	Wrong
CM	168	137	31
MHT	168	131	37

Table 2 Statistical Results of the CM-based MTT and the MHT Tracking

MULTI-SENSOR DATA FUSION IN COMMAND AND CONTROL AND THE MERIT OF ARTIFICIAL INTELLIGENCE

René G. Zuidgeest
National Aerospace Laboratory (NLR)
Anthony Fokkerweg 2
1059 CM Amsterdam
The Netherlands
Phone: +31-20-5113654
fax: +31-20-5113210
E-mail: rgzuidg@nlr.nl

0. SUMMARY

The human operator observing the real world is confronted with a huge amount of data from multiple sensor systems observing that world. Multi-sensor data fusion (MSDF) is one of the emerging fields in advanced information processing, concerned with fusing sensor data from these multiple sensor systems. Automated multi-sensor data fusion can help the operator by processing sensor data into concise and surveyable information, that is more useful than every sensor system separately can provide.
The merit of MSDF can be increased by employing the knowledge of the human operator about the real world, the sensor systems and the fusion process. With the aid of this knowledge, automated MSDF can assign meaning to sensor data and is able to reason about the observed world at a high level, comparable to what humans do.
Artificial intelligence provides techniques to represent this knowledge and to reason with it. These techniques are discussed in the context of a generic framework comprising a world model and fusion processes. These techniques can contribute to an effective updating of the world model and can support its fusion processes. In addition, a global distributed fusion architecture based on the framework is proposed. As specific domain of fusion, battlefield surveillance is considered.
This paper shows the potential use of artificial intelligence in multi-sensor data fusion.

1. INTRODUCTION

Multi-sensor data fusion (MSDF) can be considered an important field in advanced information processing [Wal90]. MSDF is the process of combining sensor data in space and time in such a way that it provides more relevant information than each sensor system separately is able to.

The increasing importance of automated MSDF is driven by a technology push as well as by a market pull. The technology of sensor systems is rapidly growing, more and more sophisticated and complex sensor systems are coming available on the market. They provide a huge amount of data, creating a need for advanced information processing through MSDF.
On the other hand, the real world is getting more and more complex [Har86]. Dissimilar sensors operating in different spectral regions are required to detect the full variety of objects present in the real world [Cha89]. For a human operator monitoring the real world through a set of dissimilar sensor systems of increasing complexity, it is a significant problem to fuse the sensor data, to assess the real world and decide on proper reactions within a limited time frame. Because of excessive data, ill-digested information and stress, wrong interpretations about the situation in the real world might be made that may have disastrous consequences.

MSDF can be applied to various domains. Domains of research at NLR are air traffic control [Blo88], multi-radar tracking employing uncertainty techniques [Don91], navigation based on Kalman filters [Pet91], battlefield surveillance [Zui92], air defence, and remote sensing.
World wide, research into MSDF is mostly performed in a military context. One domain of applied MSDF and where this paper focuses on is command and control (C^2). In this domain, commanders take decisions on the basis of fused information from various sensor systems located on and observing a battlefield. An example of a naval application in this field is the SIAP-project [Dra83]. Other applications are AMUID performing battlefield analysis on basis of sensor information [Spa83], and ECRES [Nay88, Den88] and IDA [Edw88], performing the same function, but on the basis of intelligence information (e.g. human reporting).

The wide range of delicate applications (e.g. human lives are involved in air traffic control and command and control) justifies the research into MSDF. Currently, the field of artificial intelligence (AI) is in the spot-light to support MSDF. Sensors provide only numerical data of measurable quantities (e.g. signal strength, polarisation). Processing of this numerical data and

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

performing calculations (such as calculation of the position of an object) is necessary. However, a great deal of data can be transformed to a higher symbolic level and consequently can be reasoned with in a more abstract way comparable to what humans do by using explicit knowledge about the domain. AI is a surplus value to MSDF, especially in advanced sensor control and allocation, identification of objects, assessment of the situation in the real world and prediction of future states of that world by using knowledge about objects (i.e. their structure, their relation with sensor information, their behaviour and the contexts in which they act, etc.). Systems employing AI technology could serve as an intelligent interface transforming excessive and complex (sensor) data in real-time into surveyable and relevant information for the operator [Leh86].

Chapter 2 provides a general functional architecture of an MSDF system based on a command and control model, applied to battlefield surveillance. Battlefield surveillance is considered as the continuous observation of the battlefield area to provide timely information for command and control functions.
Chapter 3 globally describes the world model that includes MSDF and knowledge about the observed world.
Chapter 4 discusses a specific set of AI techniques for representation of that knowledge and reasoning with it. These techniques emerge from knowledge-based systems (KBSs); neural networks are not considered in this paper. KBS techniques have been preferred because of their relative maturity, their ability to explain their reasoning process in a comprehensive manner (might be important in order to convince the operator) and the ease with which explicitly represented knowledge can be modified. Neural network techniques lack these important features. However, neural networks and KBSs can be complementary, where neural networks reside at a lower level of information processing than KBSs. Integration of these two techniques might provide interesting results.
Chapter 5 describes a global distributed architecture for MSDF for C^2 networks where KBS techniques and distributed AI play an important role.
Finally, Chapter 6 presents concluding remarks.

2. BATTLEFIELD SURVEILLANCE AS CONTEXT FOR MSDF

The basis of the application of MSDF in the domain of battlefield surveillance as presented in this paper is a generic C^2 model. Four command levels are identified in this model: highest, intermediate, lowest and executive. These levels have their equivalents in the Air Force, Navy and Army C^2 structure.
The data flow between the levels is cyclic. First, global tasks are generated by the highest command level, which are worked out and decomposed by the lower command levels, up to the executive. If the tasks have been executed, reporting is done all the way up to the highest command level. The C^2 cycle is closed when these reports have been assessed by the highest command level. Time and data are the most important factors that distinguishes the levels: the lower the level, the more time critical and the more detail in the data and information.

The C^2 *functions* for one command level are given in Fig. 1. Five main functions are distinguished, presented in the inner ring. A commander is tasked by a higher command level. In the context of these tasks, the current battlefield situation is analyzed. After the analysis, decisions are taken (how to implement the task) and available resources are allocated. Then the orders are prepared to task a lower command level. In the execution function, interaction takes place between the two command levels; sometimes the orders need to be readjusted because the situation has changed during preparation of orders or the commander had incomplete or wrong information. After the orders have been executed, the results are reported, a reassessment based on the report information and new sensor data is made and reporting is done to the higher command level.

The five main functions can be decomposed in a number of *processes*. These processes are displayed in the outer ring of the C^2 model. Because this paper mainly covers the first function, only the processes (1) collection of information from sensor systems and intelligence, (2) composition of the battlefield (including MSDF) and (3) analysis and assessment of the battlefield are discussed here. Note that the processes are performed in the context of the task issued by the higher command level.

The function situation analysis containing fusion and interpretation of data is currently done in the human's mind. However, because of the large amount of data which is made available by current technology and the inherent complexity of the data, it becomes more and more difficult to obtain and combine the *relevant* information out of this data stream and evaluate it properly within certain time constraints. AI provides tools and techniques for automating at least part of human knowledge. Therefore, AI can support automation of fusion processes which are now performed by the human operator. By automating low-level routinely tasks, the human operator or commander can focus on more important tasks like high-level assessment and decision-making based on interpreted fused sensor data.

Fig. 2 depicts a general architecture for battlefield surveillance incorporating automated MSDF. The architecture is based on the situation analysis function of the C^2 model. It consists of a number of geographically distributed platforms with mounted sensor systems observing the battlefield. These platforms provide symbolic sensor reports about observed events, detected objects, etc. (i.e. the sensor reports are the sensor system's output of object detection and signal-to-symbol transformation processes). These sensor reports are sent to a fusion centre (*information collection*) where they are spatially and temporally aligned (*scenario composition*) to provide a battlefield description which is then

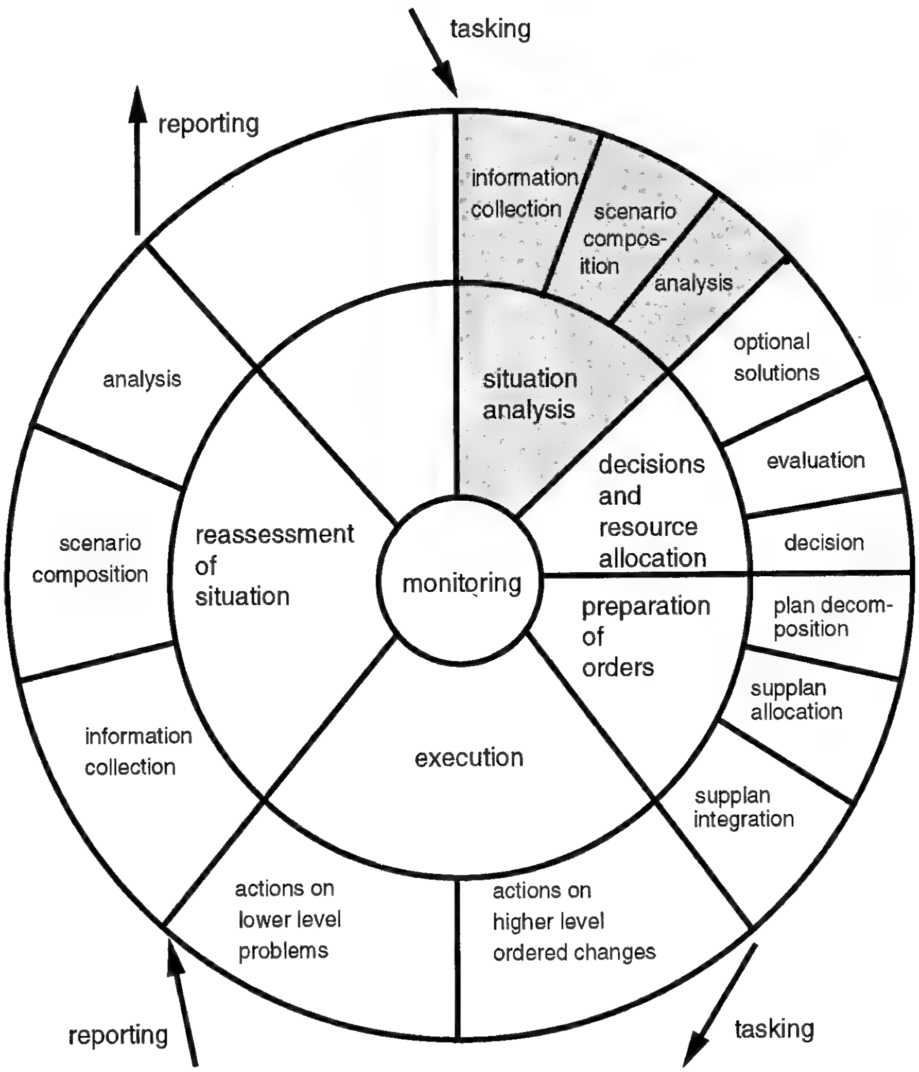


Figure 1. *A generic C² model with its functions and processes at one command level* [1].

interpreted (*analysis*) resulting in the battlefield situation description. This battlefield situation description is presented to the operator through a man-machine interface.

Based on the fusion and interpretation results, it might be needed to direct the sensor systems in order to obtain an optimal battlefield situation description. The fusion centre as well as the operator can issue requests for additional sensor information (e.g. focus on specific area) to the sensor manager. It constructs and maintains a global temporal plan in which sensors/platforms are allocated and distributes it to the sensor platforms that implement the plan.

In the following chapters, the fusion centre node containing the battlefield description is worked out in more detail.

3. WORLD MODEL AND DATA FUSION

This chapter focuses on the world model and the fusion process. These elements are located in the fusion centre node of Fig. 2. The world model is a reflection or simulation of the real world in time and space. In the context of battlefield surveillance important aspects to be represented in a world model are military objects (their structure, behaviour, and context), terrain and weather circumstances, sensing systems (their capabilities and limitations) and the relationships (e.g.

[1] This model has been developed at NLR by R.P. De Moel and B.J.P. van der Peet for an expert meeting on *Computing Technology relevant to Time Critical Command and Control Applications* (IEPG/P-3/SG-6/WG).

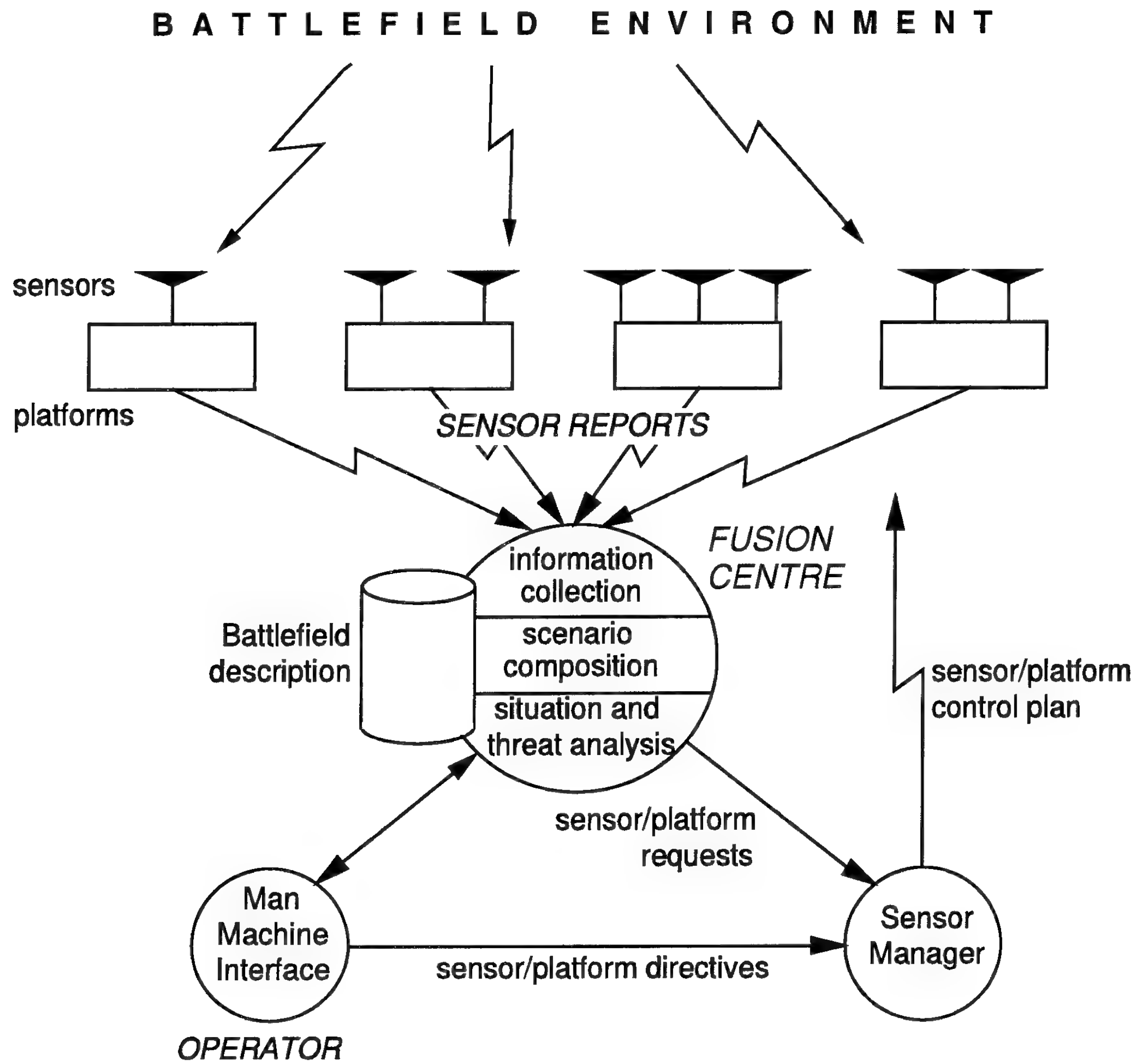


Figure 2. *A general system architecture for battlefield surveillance incorporating MSDF.*

causal effects) between these aspects (e.g. signature of object sensed by specific sensor under certain terrain/weather conditions). In addition, the world model contains inference knowledge to fuse sensor data, assess and predict object status and observed situation, identify objects, and deduce more abstract, relevant and concise information about the real world in an effective and efficient manner.

The world model has two main input streams which are categorised as bottom-up or top-down. Bottom-up data is a continuous stream of data about the real world such as (pre-processed) sensor data, weather reports, terrain conditions, and intelligence data [Gou89]. Top-down data is more discrete and consists of requests for information (from position of an object to complex *what-if* questions) issued by a human operator through a man-machine interface or by an automated system such as a resource planning system for counteractive actions. These requests initiate a top-down, goal-directed search in the world model to extract or infer the required information. In fact, the set of possible requests for specific types of information defines the purpose of the world model, i.e. to provide valid answers to questions about the real world, and hence defines - given the application domain - the construction and contents of the world model.

For the purpose of this paper, the world model is assumed to be based on a blackboard concept [Nii83, Hay85]. The blackboard concept is well-suitable for problem domains in which large amount of different source data, large number of competing hypotheses, different levels of abstraction and multiple symbolic representations are involved [Adl89]. For the problem domain MSDF in C^2 and in particular battlefield surveillance, the blackboard model consists of a blackboard information structure representing hypotheses about the real world at different levels of abstraction, and a number of knowledge sources about

the different sensor systems (e.g. ESM, Radar, IR), the battlefield environment (i.e. terrain, weather), the military domain (objects, tactics, etc.) and their inter-relationships. This chapter discusses the world model in terms of this blackboard structure and the possible fusion processes that can be incorporated in knowledge sources operating on that structure.

As information structure, a hierarchical representation fits best in which each level in the hierarchy is an abstraction of the lower. The two main reasons are the hierarchy in the fusion process (e.g. fuse sensor data into *one* object, see Section 3.2) and in the military domain. Four levels have been identified: (1) sensor level, (2) object level, (3) recognition level, and (4) relational level.
The sensor level describes the object measurements (e.g. contour and temperature), represented in sensor reports. Correlation of similar sensor reports in time results in sensor report tracks.
The object level contains information about objects on the battlefield and is the result of spatial and temporal correlation of sensor reports and sensor report tracks at the sensor level.
The recognition and the relational level comprise the tactical level in military terms. The recognition level contains military relevant information of single objects on the battlefield (e.g. identity). The relational level describes relations among objects, resulting in the detection and recognition of units or battle formations. These two levels contain information which is fully abstracted from sensor-dependent data. At these levels, *concepts* like division, tank, and the relationships among them are represented.

The knowledge sources operate on one or two levels of the blackboard (i.e. the levels of the world model). Knowledge sources can be specialized in fusing similar sensor report tracks into one object track, identifying objects from the object level to the recognition level, recognizing units, identifying representative objects within units and monitor them only, etc. These knowledge sources are responsible for the fusion of the data to higher levels of abstraction.

The next sections will discuss each level and the relationships and the fusion processes between these levels.

3.1. The sensor level

The sensor level describes object measurements (e.g. signal strength, Doppler speed, size) and characteristics about the measurement (e.g. type of sensor system, resolution, position of sensor system), which are both represented in *sensor reports*. These are the output of object detection and signal-to-symbol transformation processes of the various sensor systems mounted on platforms. The sensor level is the least abstract level of the world model. A sensor report is a low-level description of a phenomenon (a potential object or target or event that has a high degree of discrimination in relation to its environment, e.g. a hot spot indicating an engine of a tank or an explosion).

A sensor report consists of a number of attributes. Attributes concerning measurement characteristics depend on the sensor system and platform from which the sensor report originates. These are: platform ID and position, sensor system ID and type, time stamp and others like sensor performance, accuracy, and a preliminary confidence value of the observed phenomenon.
Other sensor report attributes concern measurement(s) about the detected phenomenon. These attributes, called *object features*, are symbolic representations of the signal features extracted from phenomena in the real world by a sensor system. The kind of attributes and their dimensions depend on the sensor system type and position of the platform. Table 1 shows the relation between various sensor system types, the measured signal features and the resulting object features.

Tracks of sensor reports acquired at successive times, but having similar signal/object feature values are initiated and maintained, resulting in sensor report track hypotheses. Such a hypothesis represents the belief that a set of successive sensor reports are manifestations of the same object in time. In principle, a track is formed by sensor reports from the same sensor system or similar sensor systems, because they have a common format and attributes and are, therefore, easier to correlate.

This type of fusion of sensor report into tracks happens only at the sensor level. From sensor to object level, individual sensor reports or sensor report tracks are fused into an object or object track.
Sensor report or sensor report tracks are correlated or associated to object tracks on basis of spatial data, radiometric data or the context of the sensor report. Sensor reports are correlated if their spatial references are very close or because their non-spatial object features are similar. An example of spatial fusion is the fusion of an IR and a radar sensor report track of the same platform with overlapping spatial references. An example of non-spatial fusion is the cross-section of ESM sensor reports having similar values for the non-spatial attributes (e.g. common frequency) in order to determine precise position. An example of contextual fusion is that a sensor report is part of a pattern of sensor reports (e.g. representing a column), which makes correlation based on context possible (e.g. on basis of the relative position in a column). The extent to which fusion of sensor reports and tracks can be successfully performed depends on a number of parameters such as acquisition time, object activity, density and discrimination, and sensor characteristics and performance.

3.2. The object level

The information at the object level consists of objects (or events). The objects at object level in the world model are hypotheses, expressing the belief that a set of sensor reports or sensor report tracks are concerning the same real-world object. Different sensor report tracks (possibly acquired from different types of sensor systems) may refer to the same object. At object level,

Signal feature	Object feature	Sensor system
propagation time	range	radar, laser
azimuth/elevation	azimuth/elevation	radar, IR, TV, laser, ESM
Doppler shift	velocity	radar, laser
reflected power level	Radar Cross Section	radar
polarisation	material	radar, laser
video image	contour	IR, TV, laser
frequency	frequency	ESM
modulation	modulation	ESM
	classification[2]	ESM, radar

Table 1. *Relation between signal features, object features and sensor system types.*

these tracks are fused. Moreover, for each tracked object, more abstract information is inferred on basis of knowledge about object features and how they are sensed by sensor systems and manifest in sensor data. This abstract information does not contain any specific sensor data. Examples of such information are mobility, fire capability, relation with other objects (context), etc. If enough sensor data is acquired and information is inferred, an object can be classified and promoted to the recognition level.

At the object level, tracks and features of objects are maintained and predicted. Contextual knowledge plays an important role with respect to accuracy. For example, in case of extrapolation of tracks, if an object is following a road for ten minutes (e.g, *track mode*: "road following") then the track can be extrapolated to the next crossing met. Moreover, a line of bearing (e.g. an ESM sensor report), can be crossed with the road to determine precise position under the assumption that the object is still following the road.

3.3. The recognition level

Also at the recognition level, single objects on the battlefield are described, but the information describing the objects is much more abstract and contains more military relevant information, like identity of an object and related potential capabilities (e.g. threat).

The relation of the recognition level to the object level is that an abstract name or class, for example *tank*, has been associated to the object attributes; in other words, a conceptual meaning is assigned to the objects. The recognition level consists of hypotheses about the classes to which the objects belong. This association of objects to classes has economical advantages regarding processing and memory, because the concept tank incorporates much implicit information (e.g. has a barrel, has treads, is mobile and armoured) that was explicitly represented at object level. Reasoning about a tank is easier than reasoning about a large set of - partly sensor-dependent - attributes representing the object.

Recognition is done on the basis of two types of information: (1) structural and behavioral information of the object, and (2) contextual information of the object.

The hypotheses at recognition level depend on these two types of information. Recognition based on structural and behavioral information is, for example, recognizing a tank by respectively its shape obtained from a TV sensor and the fact that it is moving. An example of recognition based on contextual information is the recognition of an object as tank on the fact it moves inside the borders of an area in which a *tank* company is operating.

3.4. The relational level

The relational level represents inter-object relations and the (tactical) situation of the area under observation. In the world model, battle formations (units) are represented by means of groupings of (military) objects and units. The relational level consists of several sub-levels, corresponding to the military hierarchy. These sub-levels are bottom-up (derived from [Kon87]): platoon, company, battalion, regiment, and division level.

Each unit in the world model is a hypothesis expressing the belief that units (or objects) at lower levels together form one coherent unit in the real world. At which level that hypothesized unit is represented, depends on the contents of the real-world unit (types of objects and numbers) and its tactical behaviour. An hypothesis

[2] Today, certain types of sensors (in particular radar and ESM) can perform preliminary classification of the detected objects. This is not considered as a signal feature, but, of course, this information should be provided in the output vector as object feature.

contains also track information. The maintenance of this information is less time critical than object level information, because the dynamics of a unit is less than of each single object. This makes tracking of units without tracking of every individual object possible, which is less difficult and saves computing resources.

Tactical, strategic and doctrinal knowledge (knowledge about the order of battle) plays an important role at this level in order to determine the status of the situation. Also, this knowledge can be used to detect and recognize units and objects according to their tactical behaviour in the order of battle (type of inference based on contextual information and knowledge).

The purpose of this level is two-fold: (1) provide the operator or commander with high-level, surveyable and comprehensible information about the battlefield for subsequent assessment and decision-making, and (2) provide the lower levels and knowledge sources the necessary context to assist and direct their inferences.

4. USING AI TECHNIQUES TO MAINTAIN THE WORLD MODEL

In Chapter 3, the world model and fusion processes incorporated in knowledge sources have been described. The information describing the battlefield situation and the knowledge used to predict possible future situations and to infer new information from old information and newly acquired sensor reports can be supported by a number of techniques from the field of AI. This chapter discusses a number of candidate AI techniques that can support the maintenance of the world model and the provision of answers on questions to this model.

4.1. Representation techniques

Chapter 3 mainly focused on the structure of the blackboard (i.e. the hierarchical representation of hypotheses), but the representation of the knowledge in the knowledge sources was not discussed.
It is unlikely that a common representation of knowledge for all the sources can be used. The lower levels (especially the sensor level) include much numerical processing algorithms and knowledge is likely to be represented implicitly in program code inside sensor data processing modules. However, at the higher levels, representation techniques from the field of AI are applicable. The most well-known are: (1) *semantic networks* suited to describe conceptual relationships (tank *is a* vehicle) and contexts, (2) *frames* to describe and model real world objects and their structure, (3) *production rules* to describe causal relationships (*if* enemy division moves to city *then* city is in danger), and (4) *scripts* to describe sequence of events (e.g. to represent military doctrine and tactics; special actions, e.g. crossing a river by a division, can reveal its organization).

4.2. Inference and control techniques

A number of inference techniques exist in deducing new information from old information using explicit knowledge. The most well-known techniques are *forward reasoning* and *backward reasoning*. Forward reasoning is typically data-driven that is heavily applied to lower levels of information processing. Acquired sensor data is quickly processed and prepared for higher level inferences. At these higher levels, more goal-directed inference techniques are applied in order to work towards a solution satisfying some goal (e.g. answering an information request from the operator) and to control the combinatorial explosion effect inherent to data-driven techniques. It is important to design a control method that keeps the number of inference steps towards an optimal solution restricted (i.e. keeping the combinatorial explosion under control) by finding the right balance between the application of data-driven and goal-driven inference techniques.
Another inference technique is *inheritance*. Inheritance is based on hierarchical relationships such as *is a* and *has a* (e.g. a tank *is a* vehicle and therefore inherits the quality that it is movable from the class vehicle, or a division *has a* battalion and therefore the velocity of the battalions is inherited by the division where they are part of).

Without sufficient control the basic inference techniques can lead to a combinatorial explosion of facts and sub-goals. Real-time performance of a knowledge-based system requires control techniques to control the inference and search processes through knowledge and information. Domain-independent search and control techniques (e.g. A^*-algorithm) as well as domain-dependent techniques (e.g. expert military knowledge for meta-level control and demons that are only activated in case of specific events) have to be employed to satisfy time constraints [Smi86, Smi89].

4.3. Techniques dealing with imperfect information

The fact that sensor systems do not provide accurate information, due to internal functioning or external conditions (e.g. weather, terrain, ECM, deception) has implications on the beliefs in the world model. The hypotheses in the world model are not a priori true and might be in contradiction to one another. This opens a discussion on how to handle imperfect information.
Information is imperfect if it has one or more of the following characteristics.

1. The information is incomplete: not everything is known. Nevertheless, conclusions may have to be drawn, possibly in the form of hypotheses. Incompleteness may be caused by: sensor coverage limited in space and time, lack of information about enemies, and non-generality of knowledge: exclusions.
2. The information is uncertain: a proposition can not be said to be true or false. Instead, only some indication of the 'belief' in a proposition can be given. Causes may be: incorrect information (e.g. false), incomplete evidence, (ir)reliability of sensor

reports, changing information (when, how?), and elapsed time (no update information).

3. The information is inexact: the information itself is intrinsically vague. This can be caused by: sensor system inaccuracies and inadequacies, processing inadequacies, navigation errors, time delays, vague expressions (temporal and spatial), etc.

Various approaches have been developed to formalize reasoning with imperfect knowledge. These approaches focus on combination and propagation of uncertainty in inferences, on detecting and resolving contradictions and on belief revision [Don91]. It appears that all these techniques have their problems.

With respect to uncertainty management, formalization of combination and propagation of uncertainty values in inferences appears to be difficult [Abr90]. For example, the *Bayesian inference theory* [Dud76] suffers from problems about assessing subjective prior distributions by humans, even if they do not know much about it, and requires evidential data to be mutually independent. The *Dempster-Shafer theory* [Sha76] is an improvement in this respect, but its formulas are complex and therefore suffers from a computational problem that could be a drawback with respect to real-time performance.

Another technique is *fuzzy logic*, which has been developed to enable reasoning with fuzzy, vague notions (*fuzzy sets*) as people do [Zad88, Hel91]. Fuzzy reasoning is not specifically geared towards real-time performance, and defining fuzzy sets and the fuzzy logic for a specific application also appears to be problematic.

Other techniques that are complementary to the techniques discussed previously focus on the fact that the real world is a dynamic world, its state changes continuously with time. This requires a continuous monitoring of the integrity of the world model. Detected contradictions (e.g. between newly acquired information and current information) need to be resolved through revision of the beliefs (i.e. hypotheses in the world model).

Two techniques dealing with revision of beliefs are *truth maintenance* and *non-monotonic reasoning.*

A Truth Maintenance System (TMS) [Doy79, Kle86] maintains the beliefs (possibly a multiple set of hypotheses, representing different beliefs about one situation) on which future inferences will be based. A TMS serves as a kind of administrative registration system. It is able to detect contradictions in the set of facts and conclusions from which they were drawn.

A non-monotonic reasoning process can withdraw specific conclusions and facts (assumptions) causing the inconsistencies (it is called non-monotonic because the set of conclusions might be smaller than before). There is a lot of research going on in developing non-monotonic logics [Roo91, Luk90], and their integration with TMSs [Rei86, Rei89]). Temporal reasoning [All84, Der83, Sho87, Zui94] is closely related to truth maintenance and non-monotonic reasoning and much research is performed in integration of these fields into one single reasoning system that detects and resolves contradictive information in time [Jou90, Sch88]. Each technique has its problems like NP-completeness of TMSs, the generality of research on non-monotonic logics and reasoning), and the frame problem in temporal reasoning.

5. GLOBAL DISTRIBUTED FUSION ARCHITECTURE

In the previous chapters, the world model within a central fusion node in the context of battlefield surveillance was discussed. The framework of the world model was based on a blackboard architecture in order to provide a surveyable insight into the information streams and fusion processes, and applicable AI techniques. For C^2 applications, one central fusion node will not be adequate. An architecture needs to be designed that in particular fulfils the following requirements.

1. *It shall support the fact that sensor systems are geographically distributed.* Communication protocols, type of data sent over (such as raw data, processed data or interpreted data), throughput, and distributed sensor management play an important role.

2. *It shall include the option that fusion might happen on platforms as well as in C^2 nodes.* Fusion might be partly performed on the sensor platform. In this case, interpreted data (e.g. object tracks) is sent over as the result. Reasons for this might be
   - to reduce data throughput which is less than if raw sensor data is sent over, or
   - to have interpreted data locally available for immediate action or accurate local sensor management.

3. *It shall be modular, reconfigurable and scalable.* This in order to be flexible with respect to
   - investigation of fusion of specific sensor combinations in an isolated manner,
   - number of deployed sensor systems,
   - characteristics of the battlefield and theatre of operations,
   - the expected sensor data throughput,
   - sensor data processing happening at different sites and/or on different machines, etc.

4. *It shall have inherent parallelism,* so that architectural elements can have private processors.

5. *It shall incorporate robustness.* If a fusion function or sensor system fails, then the system shall still be operational.

6. *The architectural framework shall be general,* and applicable to many war theatres, C^2 network structures, and application domains (e.g. crew assistance for combat aircraft [Liz88], naval domain or air defence).

The requirements rule out a centralized or sequential processing architecture. A decentralized architecture [Dem89, Dur89], based on loosely coupled, a-synchronous, course-grained, semi-autonomous agents (Fig. 3) may be better. The architecture comprises platform nodes, data fusion nodes, assessment and sensor management, and man-machine interfacing.

The platform nodes are located on and around the battlefield (ground or airborne) observing the battlefield through a number of mounted sensor systems. They

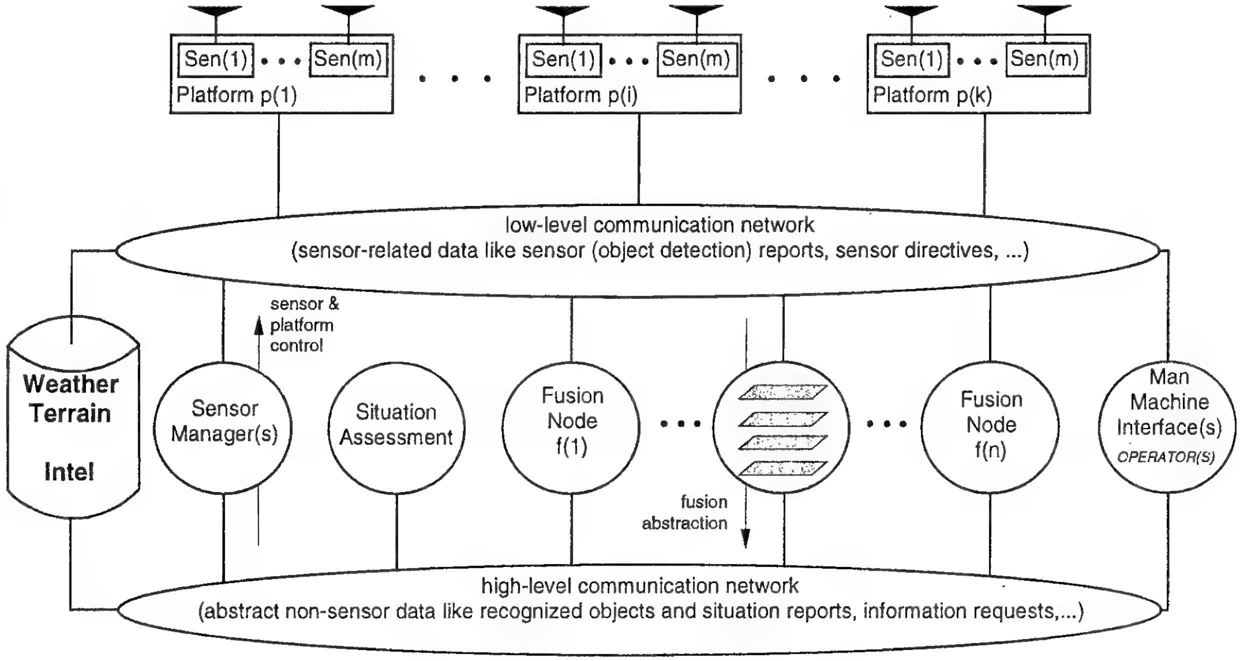


Figure 3. *Distributed architecture incorporating MSDF.*

broadcast sensor reports which are processed by the various fusion nodes.

The main function of the fusion nodes is interpretation of sensor data. All fusion nodes incorporate the world model framework as discussed in Chapter 3 and rely on conventional as well as advanced information processing techniques such as those discussed in Chapter 4. Every node might be a specific instance of a generic fusion shell, in which specific knowledge is entered that mainly depends on the set of sensors to be fused and terrain under observation; the knowledge in the world model of a fusion node that is specialized in fusing heli-borne ESM and radar reports, differs from knowledge that is specifically focused on fusing ground IR and radar. The higher levels, i.e. military and unit level, have a common representation of information, because these do not include sensor-dependent information. This enables the fusion nodes to exchange this high-level information across a communication network. In this way, the nodes can assist each other with the interpretation process. For example, one node might ask another whether it saw also a tank at a certain position *X*. If so, accuracy of the position and certainty about the identity (it is a tank) can be increased.

The findings of the fusion nodes are used as input to the situation assessment node. This node takes the high-level information of the specific fusion nodes as input for situation and threat assessment. The assessment node has been added to the architecture because it can provide the operator as well as the sensor management system high-level global information of the battlefield situation which makes well-organized decision-making and sensor management possible. In this context, small-scale situation and threat assessment is performed. An alternative is to distribute this function among the fusion nodes, eliminating centralized assessment. In this case, local assessment might be the basis for local sensor management.

The sensor management system provides feedback to the sensor systems on the basis of the findings of the other processes and the human operator. The nodes (in particular the assessment modules) and the human operator can send the sensor management system requests for sensor data. In this way, the total system is able to anticipate to battlefield situations. It does that by constructing a global plan that allocates and controls the platforms and sensor systems, based on a pre-specified plan and sensor data requests. The global plan will be distributed to the platforms where local sensor managers work out the plan.
The basic functions of the sensor management system are: (1) the monitoring of global sensor system performance, (2) the processing of sensor data requests into a plan, (3) the allocation of platforms and sensor systems and (4) the maintenance of a long-term observation strategy plan in order not to loose global observation by focusing too much and too long on local areas.
The sensor management plan could be constructed on basis of algorithmic techniques as well as advanced techniques. It can use explicit knowledge about sensor systems (e.g. with respect to terrain and weather) and AI-based planning techniques.

The final component of the architecture is the man-machine interface (MMI). Its main goal is to depict in a

surveyable manner the battlefield situation, mainly based on the information in the assessment node. If necessary, the operator can consult other systems or nodes represented in the architecture. Through the MMI, the operator can directly influence the sensor management plan.

The distributed architecture of agents discussed in this chapter opens the world of distributed artificial intelligence (DAI) and processing [Les83]. This key technology fits very well to the inherent distributeness of the C^2 process. Several alternatives are possible to map this architecture or multiple instances of it [Adl89] on existing C^2 networks. For example, each C^2 node in a network may have co-located a number of sensor systems, one or more fusion nodes to fuse the sensor data, an assessment node, a sensor manager to control the sensors and an MMI. In addition, a communication module should be available in order to exchange information (battlefield information, sensor control plan, etc.) with other C^2 nodes. Important questions to be solved are the way of communication between the various agents and between C^2 nodes (locally as well as globally) and how to perform conflict resolution in order to achieve globally coherent behaviour of the C^2 network of data fusion systems [Pol93].

To conclude this chapter, note that the system architecture fulfils the requirements.

- It copes with geographically distributed sensor systems.
- It is modular, reconfigurable and scalable. The modules can be situated on platforms as well as in C^2 nodes and can be installed on separate hardware. Furthermore, if extra sensor systems are placed in the field, an extra fusion node can be created and added, based on the same framework as the others. If the set of sensor systems or the operational theatres changes, the architecture still holds, the main thing to do is to down load new data and knowledge into the various data bases and knowledge sources about the used sensor systems and operational theatre such as tactical data and terrain/weather data.
- The architecture also incorporates robustness in case of failure. If a sensor system or fusion node fails, the system will still be operational. It is preferred that each element in architecture runs on private hardware, so that a hardware failure will not shutdown the complete system. Beside this, real-time performance is increased because processing is distributed among multiple parallel machines.
- And finally, it is thought that the architecture is flexible enough that it can be applied to many battlefield situations and operational theatres, such as the naval domain or air defence.

6. CONCLUDING REMARKS

This paper describes the potential use of artificial intelligence to enhance multi-sensor data fusion in the field of C^2. A C^2 model has been presented, and the place of MSDF in this model has been discussed. Knowledge about the domain of fusion can contribute to better performance of data fusion. To mention some basic pieces of knowledge that can support dat fusion processes:

- knowledge on sensor systems and how they operate, given the terrain and weather conditions and objects to be detected,
- knowledge on the manifestation of objects in different types of sensor data,
- knowledge on typical contexts of an object (for example with which objects it usually cooperates),
- and knowledge on tactics and doctrines to infer and assess the battlefield situation.

AI techniques using this knowledge can aid in effective control of the platform suite and in directing the fusion processes by only focusing on relevant parts of sensor data instead of processing and fusing all information that is offered by the sensor systems.

Because of the explicit representation of knowledge, it is expected that a fusion application in battlefield surveillance can be relatively easily transformed into e.g. a naval application by "only" replacing the knowledge. Flexibility and adaptability is provided in case of changing military context by replacing the knowledge depending on the theatre of operations.
The framework of a distributed architecture with its multiple communicating agents and incorporated AI techniques remains valid in many other applications, e.g. crew assistance for combat aircraft. For the Air Force, the link between battlefield surveillance and e.g. Close Air Support, Battlefield Air Interdiction and Air Reconnaissance missions should be clear.

Research of application of AI in domains like C^2 should be encouraged, especially with respect to real-time performance and integration into C^2 infrastructure with its existing computer systems which are mostly based on conventional technology [Leh86, Sch88]. In this respect, techniques of major concern are representation and inference techniques, and techniques dealing with uncertainty. In addition, distributed problem solving techniques and related architectural solutions like the blackboard model are equally important. Further research should actually prove the usefulness of AI and the maturity and applicability of its techniques in the domain of multi-sensor data fusion.

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AIDEX: AN EXPERT SYSTEM FOR AIRCRAFT IDENTIFICATION

J. Ebmeyer
H. Freyler
Siemens AG
Defence Electronics
Air Defence
P.O. Box 1661
85705 Unterschleißheim
Federal Republic of Germany

Summary

The AIDEX expert system is the first expert system developed for aircraft identification providing a knowledge-based fusion of identification data from various sensors and identification sources.

Keywords

- Artificial Intelligence
- Expert System
- Identification (of aircraft)
- Knowledge based Systems
- Recognized Air Picture
- Recognized Air Picture Production

Abbrevations

AIDEX: Advanced Identification Expert System
ACM: Airspace Control Means
AP: Air Picture
ARO: Auxiliary Read Out
CRC: Command and Reporting Center
GEADGE: German Air Defence Ground Environment
IFF: Identification Friend/Foe
ID: Identity
ID-Source: Identification Source
IDO: Identification Officer
KBS: Knowledge Based System
MIP: Mission Plan
MMI: Man Machine Interface
PPI: Plan Position Indicator
RAP: Recognized Air Picture
RAPP: Recognized Air Picture Production
RT: Radio and Telephonie
SIG(INT): Signal Intelligence
XPS: Expert System

Contents:

1. Preface and Introduction

Day-to-day tasks in the CRC show that operating personnel are overburdoned in many aspects.

A good example of this is the IDO whose duties include identifying all air tracks in the CRC area of operational responsibility (AOR). His excessive workload results from the high level of air activity and the volume of information received from the various identification sources.

Automation is urgently needed for these duties. Since complex decision processes are involved, based on the expertise and experience of the IDO, this application is a good example for using expert systems.

2. Objective

The development of the AIDEX system pursued several goals:

- Improving the identificiation process
- Usage of expert systems under real-time constraints

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

- Evaluation of user acceptance
- Evaluation of operational benefits.

3. Conventional and Knowledge Based Systems

The primary difference between knowledge based systems and conventional software relates to the separation of the expert knowledge from the implementation knowledge of the software specialist. The expert knowledge is stored in knowledge bases. The techniques for processing this knowledge are separately implemented in the inference engine (see Fig. 1).

The advantage of this clear separation of knowledge and knowledge processing is the possibility to keep the expert knowledge intelligible to the user by its presentation in a virtually natural language. Through situation dependent chaining of knowledge elements, the inference engine can also construct solution paths which have not been explicitly specified by the developer.

The explanation component allows the user to follow how the system has achieved a particular solution.

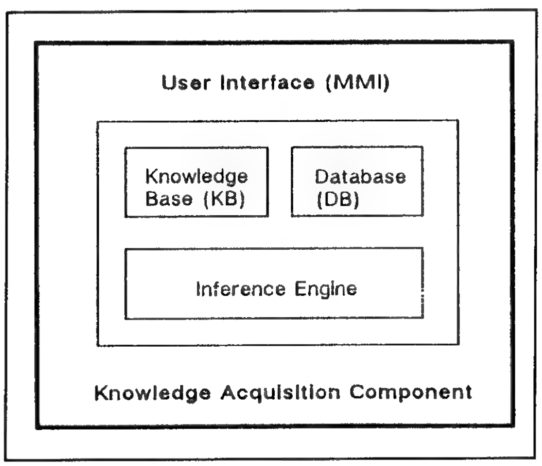

Fig. 1: Components of an expert system

4. Identification Sources

The AIDEX expert system processes ID data from the same sources as are currently available to an IDO (see Fig. 2). These include radar data (incl. IFF), ID sources such as Mission Plans, Signal Intelligence and Radio Telephonie messages (from own pilots). Additional information such as SIF codes, alarm states and Air Space Control Means are also incorporated into the fusion process.

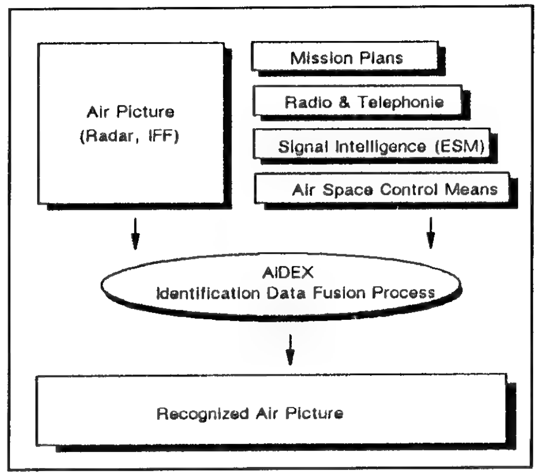

Fig.2: Information sources and identification process.

5. System Architecture

The AIDEX system consists of the three main components

- correlation
- fusion and
- user interface.

The ID information from Air Space Control Means, Mission Plans, SIGINT and Radio Telephonie are correlated with the radar tracks in order to process all information relating to a given track.

The correlation function is performed by neural networks. The actual fusion of the ID Data is performed by the expert system.

The inference engine controls the fusion process ant the application of the identification rules contained in the knowledge bases (see Fig. 3).

The AIDEX system is controlled via two 19'' screens, a keyboard and a mouse. One screen (the Plan Position Indicator) displays the air situation, whereas the access to operational functions is realized by specific menus. The second screen (Auxiliary Read Out) displays aphanumeric information such as track data, ID information and explanations related to system decisions.

In case of conflict occurance the operator is automatically alerted

AIDEX runs on standard UNIX computers under C++, the man machine interface is realized by X-Designer.

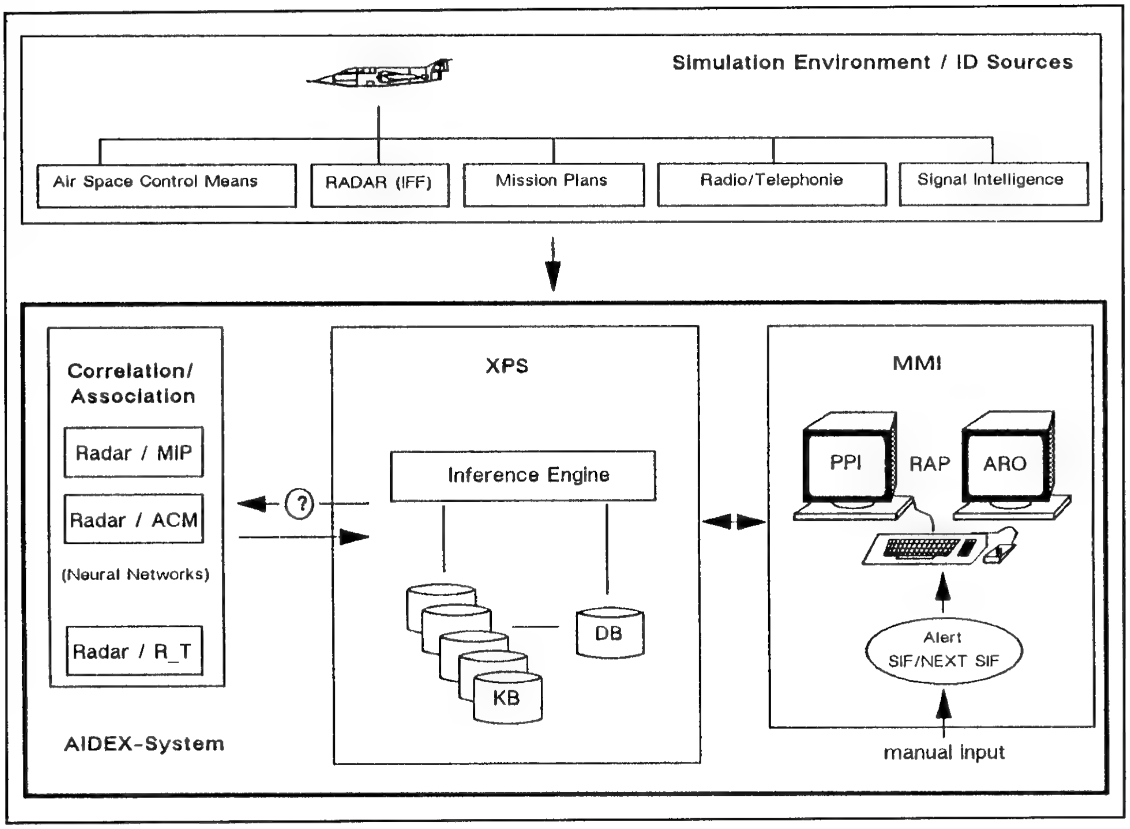

Fig. 3: AIDEX System Architecture

6. Knowledge Acquisition

The quality of the results obtained from an expert system is determined by the expertise stored in the knowledge base. Therefore, the AIDEX system was developed in close cooperation with military experts. The knowledge bases contain the current NATO identification rules and the empirical knowledge of the IDOs.

AIDEX is a real-time capable expert system. The real-time performance is achieved by

- efficient software structure/ programming
- speeding up the inference process
- problem based planning of the solution method.

The structured form of the implemented knowledge is distributed among several knowledge bases in order to ensure higher transparency and more processing efficiency. This ensures that the system can be quickly adapted to different ID criteria, such as may be important for crisis reaction forces.

7. Field Test

AIDEX was testet in two German Command and Control Centers during a field test in 1993. Air Picture, ID sources and -information were provided by a simulation environment both to the IDO crews and the AIDEX system (see Fig. 4). Operator actions, manual identifications and the results of the AIDEX system where recorded by GEADGE- and AIDEX recording software. An evaluation was done concerning criteria as follow:

- load capacity
- identification quality
- processing of difficult problems
- system reliability
- user acceptance.

This field test showed that an expert system is capable of supporting an IDO substantially and that the AIDEX system processes the identification task in real time. The ID quality of the system and the complexity of knowledge processing has achieved a level comparable with that of a trained IDO.

Operating staff welcomes the AIDEX system as a valuable means of support in the identification process.

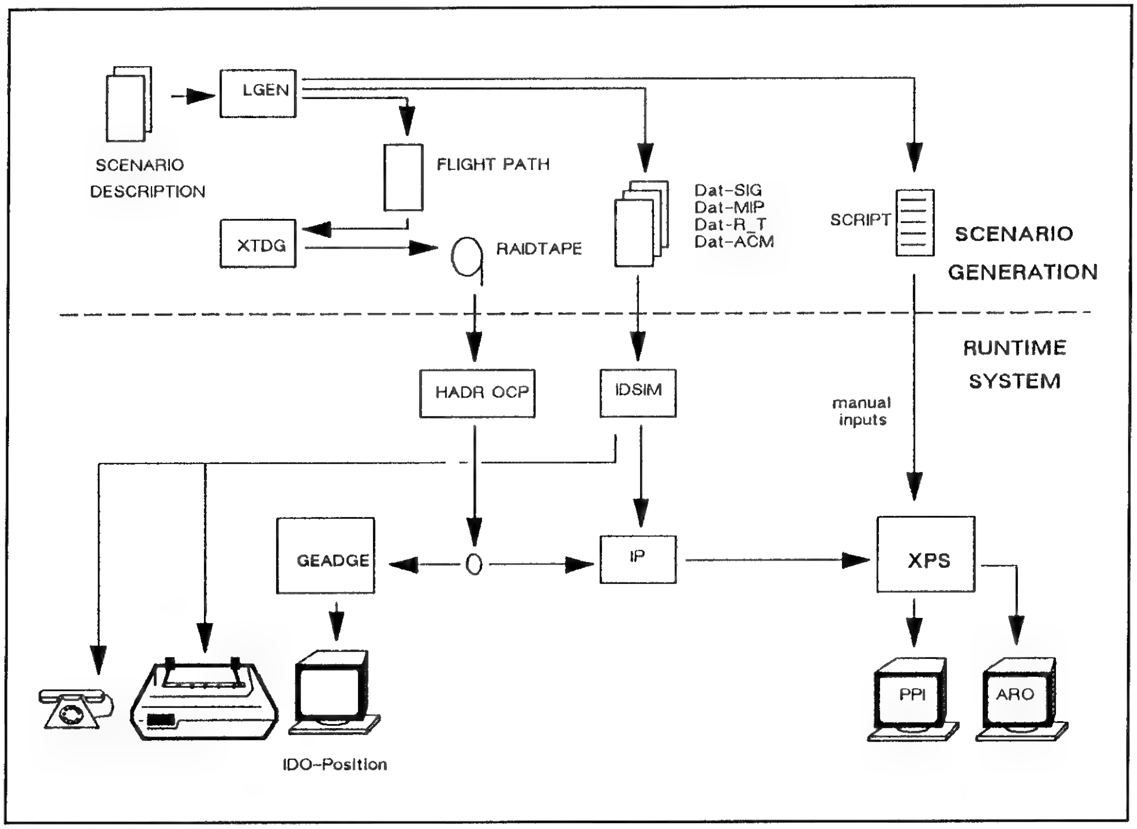

Fig. 4: Configuration of simulation environment, GEADGE and AIDEX during the field test in a Command and Reporting Center

8. Future Development

The AIDEX expert system is being extended for processing additional ID-sources and -information which are available for the identification in peacetime such as

- Flight Plans:
  - ADMAR 2000
  - ZKSD
  - AFTN
- ATC (Air Traffic Control)
- ICAO Data.

The knowledge required for peacetime identification will be acquired and implemented as new knowledge bases.

In order to prepare the AIDEX system for installation in Command and Reporting Centers or mobile shelters it will be connected to a modern Multi Sensor Tracker.

Architecture and implementation of a multi-sensor data fusion demonstration model within the real-time combat system of the Canadian Patrol Frigate

F. Bégin, E. Boily, T. Mignacca, E. Shahbazian, P. Valin
UNISYS GSG Canada, Inc.,
6111 avenue Royalmount,
Montréal (Québec)
H4P 1K6

1. SUMMARY

The research and development (R&D) group at UNISYS Government Systems Group (GSG) Canada is working on a demonstration model of a multi-sensor data fusion (MSDF) implementation for the Canadian Patrol Frigate (CPF). The conditions are made very realistic by the use of the Software Test and Development Facility (STDF) situated on the premises in Montréal. The paper describes the implementation design of the system. More emphasis is put on the architecture of both the simulation and the fusion systems. The fusion system is divided into four processes: Information Management (IM), Multi-Sensor data Fusion (MSDF), Performance Evaluation (PE) and Display Management (DM). Each process within the fusion system is outlined.

2. INTRODUCTION

Future Combat Systems (CS) must improve their tactical performance in order to keep pace with the continual improvement of the threats. The refinement of position and identity estimation as well as situation and threat assesment are fundamental elements of this amelioration. Multi-Sensor Data Fusion achieves this goal through the association, correlation and combination of data and information from multiple sources. This has to be performed exhautively and in a timely fashion.

A number of R&D programs studying the various aspects of the MSDF technology in preparation for the mid-life upgrade of the Canadian Patrol Frigate has been completed by UNISYS GSG Canada. Some of these were funded by Chief of Research and Development (CRAD), and some performed as independent internal R&D (IRAD). The largest of these programs is the development of the MSDF system demonstration model fusing nearly all sensor data of the CPF within the STDF real-time naval Command and Control System (CCS) at UNISYS plant in Montréal. This project will:

- help better understand the issues of fusion for dissimilar sensors onboard a single platform,
- allow analysis of various Operator-Machine Interface (OMI) strategies to display the fused data,
- develop a set of performance evaluation criteria for a CCS employing an MSDF system, and
- implement modular fusion software programs which can be easily updated to include future advances in fusion algorithms.

This paper first presents the environment in which the fusion project is being developed and then describes the evolving software architecture design and implementation.

3. ENVIRONMENT

3.1 STDF simulation and operation

The CPF CCS has a distributed computer architecture, where 30 AN/UYK-507 computers (each rated at slightly over 5 Million Instructions per Second) are connected via a 10 megabit/second bandwidth Shipboard Integrated Processing and Display System (SHINPADS) serial data bus. The STDF has been built within the 1,486 m^2 RF-shielded enclosure at Paramax in Montréal to certify and maintain the CPF CCS software. Figure 1 below describes the STDF system. It consists of two subsystems which have identical distributed computer architecture:

1. Simulation System, which simulates the environmental, target and weapon information.
2. Operations System, which is a full scale CPF CCS.

The full CCS at the top of Figure 1, without the MSDF processor and the network monitor node at the right, is fully equivalent to the system on board the CPF. The simulation system shown at the bottom of the figure exists only in the RF shield. A function running on one of the processors on the SIM SHINPADS bus generates sensor data corresponding to a scenario (pre-recorded or real time generated). Other functions, distributed on the rest of the processors, use the identical scenario data distributed to all processors on the SIM SHINPADS to generate outputs that each corresponding sensor would give in the situation. The functions in the operations system (top part) treat the sensor data as the real CCS system would. The function in charge of the display takes that information from the CCS global database (GDB) distributed to all the CCS processors over the SHINPADS bus and displays it on the screen according to CPF military standards.

Certification of the CPF CCS software requires repeatability of the simulated scenario. To insure this repeatability, the simulated sensor signal is noiseless. For example, all the simulated radar tracks contain exact position. Some smearing needs to be applied to transform these noiseless tracks into more realistic contact-like data that can then be input to the MSDF function.

3.2 MSDF input data

As can be seen in Figure 1, the data received by the MSDF processor is taken from the CCS SHINPADS bus. A network monitor node captures the messages of interest and then inputs to the MSDF processor (SUN Sparc-10) through an interface card (GET Engineering's SBus to NTDS Parallel interface). The CCS information is already filtered by the Automatic Detection and Tracking (ADT) software of the radar or the CANEWS. This pre-filtering hides some information from the MSDF processor and will obviously limit the fusion potential of the whole system.

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

The design and implementation of this MSDF demonstration model was not intended to address any memory or CPU limitations since it is not expected to be ported directly to the CPF. Our choice of a suitable computer platform was then restricted only by our vision of future trends in computer chip design and operating systems. The current market evolution towards RISC based processors, and the emergence of UNIX like operating systems as the industry-wide standard, makes the SUN Sparc-10 a natural choice. It has the added desirable features of possible upgrades with multiple processors and the expected ruggedization of such chips and platforms in the near future.

Table 1 describes all the information of interest to the MSDF process that can be found on the CCS SHINPADS data bus. The information can be divided into 3 parts: positional, attribute and general information. The first two sensors (SG-150 and SPS-49) are medium and long range radars (MRR and LRR) which provide the positional information. The CANEWS is an electronic support measure (ESM). It provides the attribute information along with the communication intercept operator (CIO) and two identification friend or foe (IFF) transponder systems slaved to the radars. The general information comes from the CCS data base (e.g. own ship velocity).

The "input to MSDF" column in Table 1 describes the information provided by each sensor. Some of these quantities are constants and are not transmitted on the SHINPADS bus. They are simply stored in a configuration file along with other reconfigurable parameters. Furthermore, the radar detection errors (constant inputs) are multiplied by a scaling factor (2/3). This factor is ad hoc and tries to take into account the effect of pre-filtering of the radar data.

For simplicity in this version of the MSDF process, the CIO information is not used. We expect to include the CIO in a later version of the program.

It is important to note that the pre-filtered radar data does not include a complete covariance matrix. This matrix would be

Table 1. Available sensor data on the STDF operation bus.

Sensors	Input to MSDF
SG-150 (MRR)	Track Number ν, time of arrival T, Range R, $\sigma_R = 2\times15/3$ m, Beam number, Bearing β, $\sigma_\beta = 2\times0.17°/3$, speed components v_x and v_y, $\sigma_{v_x} = \sigma_{v_y} = 50$ km/hr.
SPS-49 (LRR)	ν, T, R, $\sigma_R = 2\times60/3$ m, β, $\sigma_\beta = 2\times0.5°/3$, v_x and v_y, $\sigma_{v_x} = \sigma_{v_y} = 150$ km/hr.
CANEWS (ESM)	Emitter Number, T, β, σ_β, Identity declaration, confidence on declaration.
CIO	Signal number, T, β, σ_β, Identity declaration, confidence on declaration.
AN/TPX-54 IFF	Contact number, T, R, σ_R, β, σ_β, response, mode, confidence on response.
CCS	Ownship velocity and position

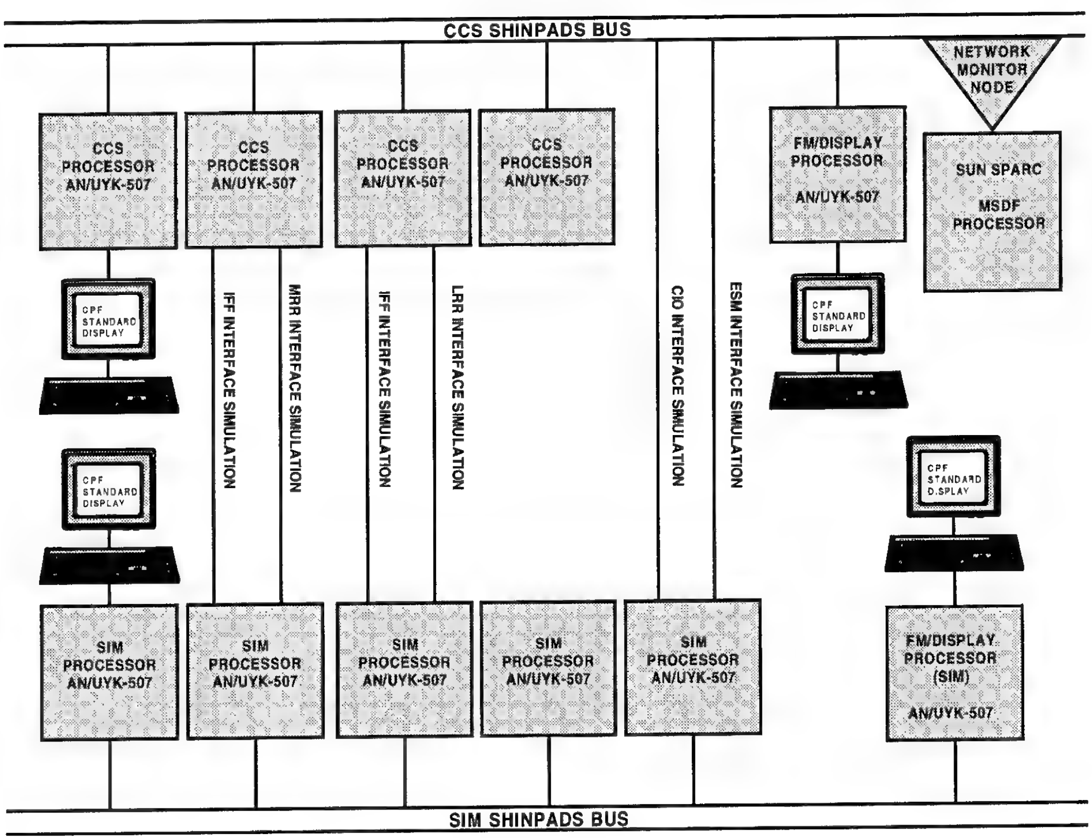

Figure 1. The CPF STDF used as the MSDF simulation facility.

required to perform a true track-to-track MSDF function. The absence of noise in the simulated sensor data should also be noted. For the purposes of MSDF processing, some random noise is added to the radar data within the CCS system. This is done before providing the data to the CCS functions as well as to the MSDF processor over the SHINPADS bus. This noise permits the evaluation of the MSDF algorithms.

4. SYSTEM IMPLEMENTATION

Two main types of fusion architectures exist, based on the level at which the sensor data is processed: sensor-level and central-level [Reiner, 1985, Blackman, 1986].

The central-level fusion uses the data detected directly from the sensor. Each sensor transmits its observations with negligible delay, through large bandwidth communication links, to the fusion center where the association of the multisensor data and state estimation are performed to generate composite tracks.

Sensor-level or track-to-track fusion is based on an independent detection and state estimation performed within the signal processor and tracker of each sensor. The tracks in the sensor track file would be established primarily based on measurements received from the individual sensor. These sensor-level tracks are then combined into a central track file. Within sensor-level fusion architecture, there are two fundamentally different methods of integrating data from multiple sensors : fusion with hard-decision sensors (also called hard fusion) and fusion with soft-decision sensors (also called soft fusion).

Hard-decision sensors measure signals and return yes/no responses (declarations) based upon decision criteria within each sensor. That decision is reported to the fusion center. On the other hand, soft-decision sensors return a measure of the confidence (such as a probability) that quantifies the uncertainty in detection and/or identification. Soft-decision sensors quantitatively "classify" the measured data. They report multiple hypothesis to the fusion center with a measure of uncertainty or confidence value for each hypothesis [Buede and Waltz, 1989].

The implementation of the MSDF System is as modular as possible to make it simpler to program, to permit to eventually retarget modules on different processors (if required) and to encapsulate the functions related to each module. Figure 2 shows the top level data flow diagram of the MSDF System software. Each of the individual modules (shaded boxes) are implemented as independent UNIX processes and coded in C except for the MSDF process which is coded in Ada. These processes communicate with each other using UNIX System V Inter-Process Communication (IPC) queues, shared memory segments and semaphores. The queues provide direct synchronous communication between modules (e.g. IM sends sensor data to MSDF). The shared memory segments hold the databases for asynchronous communication and for fast communication of large streams of data. The semaphores are used to prevent collision while accessing the databases. There is one semaphore for each database and one external queue for each of IM, MSDF and PE. There is no need for a queue for the DM process since all its inputs are achieved through database access. Since DM is the OMI, it can send command

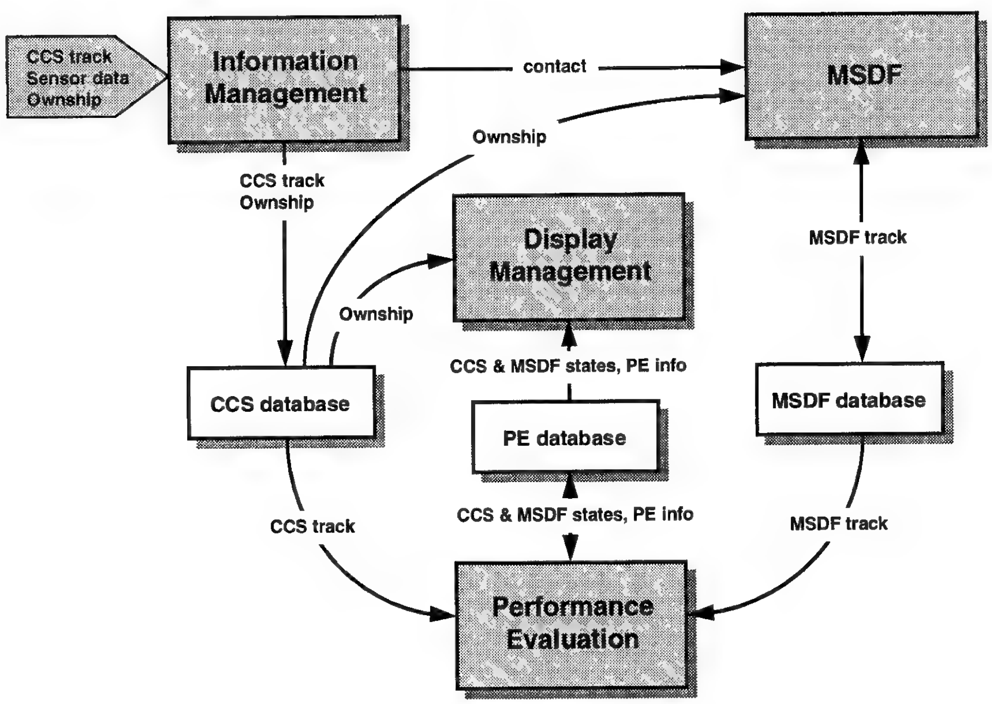

Figure 2. Diagrammatic structure of the MSDF System. The grey boxes represent the processes while the white boxes represent the databases. The type of data exchanged between the processes themselves or between the processes and the databases is also shown. The command messages issued from the DM process are not shown but DM can send commands to any other process.

messages to the other modules (e.g. 'quit' or 'change this parameter for that new value').

Basically the overall operational functionality of the system is as follows: the information management process (IM) reads the appropriate data from the SHINPADS bus and formats it into a message structure or a database structure according to the type of the data read. If the data read is a sensor data, it sends it as a contact to the MSDF process. However, if the data read is Ownship information or CCS track, it stores it in the CCS database. Upon receipt of the contacts, the MSDF process aligns and associates them to tracks previously stored in the MSDF database. The contacts are fused with the appropriate MSDF tracks and the MSDF database is then updated accordingly. The PE process wakes up periodically, reads both the CCS and MSDF databases, performs some comparison tests and criteria computation for the two systems and updates its own database with the results. The DM process takes care of displaying the information of interest according to the military standards used on CPF and also displays some real-time performance evaluation results. Moreover, DM provides the STDF MSDF operator with control of all of the MSDF system's functions via quick action buttons (QAB). The displayed information is mainly read from the PE database. More details on IM, MSDF, PE and DM are presented in the following sections 4.1 to 4.4.

4.1 IM

The IM process provides the interface processing between the SHINPADS bus and the MSDF processor. The functional diagram of the IM process is provided in Figure 3.

As can be seen in this figure, IM consists of two independent sub-processes: IM1 and IM2. IM1 rapidly reads from the interface card, pre-filters the data required for the MSDF Sustem and immediatly sends the selected data to IM2 via an IPC queue which serves as a buffer between the two sub-processes. This design was chosen to ensure that the incoming data from the SHINPADS bus is processed with minimal delay, since the data buffers in both the network monitor node and the GET card are limited and can lose data, if overflowed. The UNIX priority of the IM1–IM2 sub-processes as well as the length of the queue between IM1 and IM2 can be optimized to handle maximum data rates possible from the SHINPADS bus.

The IM1 process first initializes the network monitor node (NMN) via the GET card to emulate one of the CCS processors to be able to accept CCS data. Since processes within the MSDF processor require only a subset of the data available to the CCS processors, IM1 filters out all the unnecessary data, and sends the pertinent information to the IM2 queue as follows:

1. CPF CCS vehicular track data (position, velocity, time of detection, etc.), identification data, and Ownship data (position, velocity, heading, roll, pitch, etc.),
2. Sensor interface data as shown on Table 1.

Note that, as stated above, the radar data includes some random noise. The CCS vehicular tracks are established by the CCS functions and also from the radar data that contains this noise.

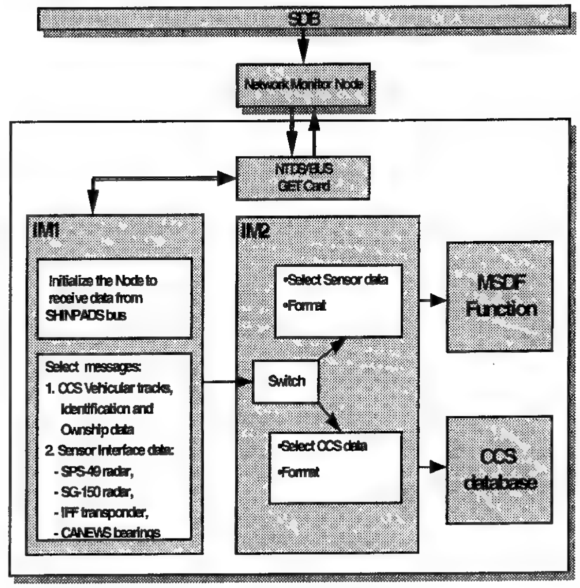

Figure 3. Functional diagram of IM process.

The IM2 process reads the SHINPADS data messages from its queue, sorts them by their type, CCS data or sensor interface data, and processes them as follows:

1. The CCS data is formatted. Only the data components necessary for the MSDF, PE and DM processes are saved in the CCS database.
2. The sensor interface data is formatted. Only the information necessary for the MSDF process are sent to the MSDF process queue.

The CPF CCS has a history recording (HR) function, which allows recording of any selected information onto a tape as it performs a trial. Another version of the IM1 process can be developed to use such a HR tape as input, where the CCS vehicular track, identification, Ownship, and sensor interface data have been recorded during trials. The added advantage of having the IM split into two processes is that this modification to use HR data as input for MSDF will only affect the IM1, and will require minimal effort.

After the MSDF processes have been integrated and evaluated in STDF, the HR tapes will demonstrate the MSDF function performance using real sensor data in real scenarios.

4.2 MSDF

The MSDF process is subdivided into four parts as shown in Figure 4: data alignment, gating and data association, position update and identity estimation. The fusion process itself is integrated with the state estimation and the identity estimation processes. We will give a simplified description of these parts.

Data Alignment: The positional information reported by the sensors do not have the same origin. Spatial alignment is performed for the SPS-49 radar and the IFF. The SG-150 position is considered at the origin and a parallax correction of the SPS-49 is performed for the reported range and bearing. Time alignment is performed to extrapolate the MSDF tracks to the time of the reported contact, which is also the MSDF fusion time.

Gating and data association: The radar "contacts" are coming in buffers (lists). These buffers correspond to a spatial sector around the ship. The gating process first assigns to each contact in the buffer a list of tracks from the MSDF database. The assignment is done by searching which contacts are in each track's gate. Track gates are error zones around the track's estimated position (note that the radar track velocity is also used for gating). Singleton associations are performed to take care of all pairs of tracks and contacts which trivially associate together (only one contact in a track's gate and no other contact for that track). The category of the track and contact pair (air or surface) is also compared for selecting singleton associations. Then the association process calculates an assignment matrix to express the cost of the remaining potential contact-track pairs. The cost is the statistical distance between a track and a contact. Many types of methods can be used to solve the linear assignment problem arising from this nearest neighbour association. The JVC algorithm has been shown to be the most appropriate algorithm for this implementation [Drummond, Castanon and Bellovin, 1990]. The JVC algorithm is a JV algorithm optimised for sparse matrices [Jonker R. and Volgenant A., 1987]. The association process ends by fine tuning the time update of the contact in each pair. This is to ensure that both the contact and the track within the pair have the same time index.

Position update: The State Update uses two linearized and adaptive parallel Kalman filters [Bourassa *et al*, 1993]. The inputs to this process are respectively a track position (in cartesian coordinates x,y), a measured contact (in polar coordinates r, θ) and the time interval since the last update (Δt). The output (state vector) is an updated track consisting of the new estimated position (x,y), velocity and covariance matrix.

The parallel filters technique was chosen because it ensures more reliable tracking than a single filter especially when the target is manoeuvring. The two Kalman fiters use different plant noise. The first filter is optimised to track a non manoeuvering target and the second one takes care of the manoeuvres. These manoeuvres manifest themselves as large low-probability innovations. This avoids the frequent re-initializations that a single filter would have to do. These re-initializations would introduce an error in the state estimates (position and velocity) for several scans. The state update process finally sends the velocity to the identity estimation process.

Identity estimation: The details of this process for this implementation were presented at the AGARD 66th symposium on Challenge of Future EW System Design [Simard *et al*, 1993]. A truncated version of the Dempster-Shafer algorithm has been selected for the implementation.

The typical attribute information fused are the target speed from the positional data fusion, the target class from the radars and IFF, the target allegiance from the IFF, the emitter composition from the CANEWS (simulated from a list extracted from Jane's). The platform database (PDB) is built from Jane's and excludes acceleration and radar cross-section.

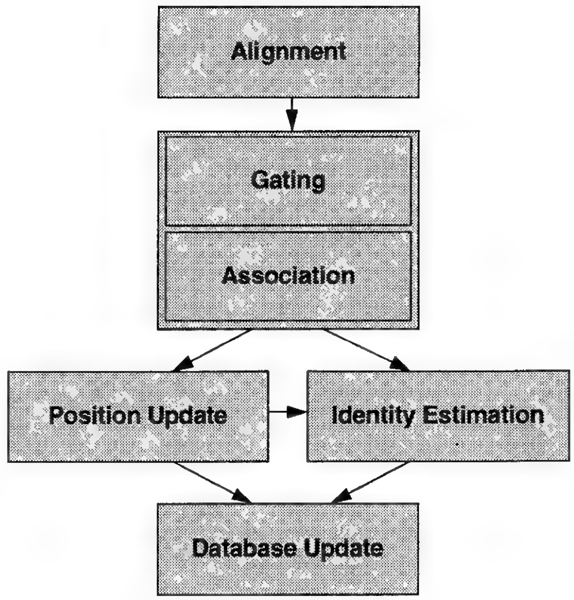

Figure 4. The main components of the data fusion process.

Some complex generic propositions are of special interest to a commander. These generic propositions are related to types of attributes such as: allegiance (friend, foe or neutral), origin (Canadian, US or other country), air type (helicopter, missile, attack aircraft), threat level (very high, high, medium, harmless).

4.3 PE

The goal of the performance evaluation process is to produce data in order to measure and analyse the relative and absolute performances of the MSDF System versus the CPF CCS. The measurement is done in terms of pre-determined specific criteria whose computed values can either be directly used in real time to get a measure of performance or be used in a later off-line analysis phase. The specific criteria are designed to evaluate the performance in terms of tracking, identification and system general issues (e.g. tactical criteria, information quality criteria). The criteria have been presented in more detail elsewhere [Boily, 1994] and will not be repeated here.

Basically, as shown in Figure 5, the PE process is a dormant task which wakes up periodically (triggered by an external forked task sending it an IPC message), reads the CCS and the MSDF databases, aligns the data read from the databases, computes a number of criteria, saves the results in the PE database and gets back to its dormant state waiting for another message. The data alignment is done in two parts: the time update of the state vectors of both CCS and MSDF tracks, the track-to-track association between the CCS tracks and the MSDF tracks. A brief description of these parts follows.

Time update: This first part is performed in order to bring the state vector of both CCS and MSDF tracks to the exact same moment, permitting error-free track-to-track association (described below) and simultaneous performance evaluation for both CCS and MSDF systems in the same time frame. The time update is a linear projection without acceleration of both the state vector and the covariance matrix.

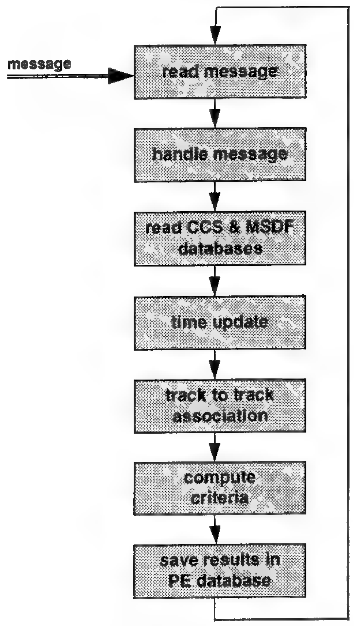

Figure 5. General block diagram of the PE process. The control point is dormant in the 'read message' function and is triggered to resume by any incoming message.

Track association: Since some comparison of the performances of the actual CCS to the MSDF system is done on a track-to-track basis, it is important to compare the track numbers that correspond to the same target. The track association is done on a proximity basis in both position space and velocity space. Two gates are then used, one for position and one for velocity, and tracks numbers of different systems are associated if they are unambiguously in the same gates. In case of ambiguity (more than one track of a particular system in the same gates) the previous track number association prevails.

When the time update and the track association have been done, it is possible to compute the performance evaluation criteria. Each criteria computation has its own independent configurable periodicity and some criteria have externally configurable parameters.

Triggering messages can be new configuration parameters from DM or messages sent by a special external timer process previously forked by PE. This timer has knowledge of all the criteria periodicities and sends triggering messages to the PE queue when the time has come to compute a criteria.

There are some constraints imposed on the PE criteria because of the limitations in available data. Some tests that we would like to perform cannot be implemented because the relevant data are not available from the CCS bus. One example of unavailable data is the covariance matrices of the CCS state vector which are computed by the ADT of each radar but are not broadcasted on the bus. Basic direct comparison of the CCS and MSDF covariances matrices would have been a precise indicator of the precision of the tracking of both systems. We must approximate the CCS covariances matrices from the typical measurement error associated to each radar in order to perform this kind of evaluation.

The simulated 'ground truth' data is also not available on-line, while the scenario is running. For the current implementation, the simulated 'ground truth' is available through a file after the scenario is completed. This limits the type of PE criteria that can be calculated and reviewed on-line. Most on-line comparison between CCS and MSDF must be relative to CCS.

4.4 DM

DM is the OMI module which integrates and controls all MSDF functions (MSDF, PE, IM and DM). DM was developed using UIM/X[1], a graphical user interface (GUI) builder with OSF/Motif[2] Widgets in a UNIX environment. The functionality and appearance of the DM module is determined by the CPF standard military display.

DM is the top level module of the MSDF system, and as such, it must manage all other modules. DM must initialize all system modules (using UNIX system calls), create all queues, semaphores and shared memory segments required for communication between modules during run-time. DM must also dispose of the above upon exiting the system. The user can control which MSDF modules are enabled and can reset them during run-time.

The six areas of the display are shown in Figure 6. Vertically and from the upper left corner, we see the Close Control Readout (CCRO) and Data Amplification Readout (DARO) areas which provide detailed information about a selected target. The Operator Guidance Readout area (OGRO) allows user interaction with PE and MSDF by prompting for values of specific configurable internal parameters. DM enables users to navigate through four QAB arrays. Each QAB array consists of a matrix of buttons, which permits the user to select the desired system functionality. Tracks and associated information are represented graphically in the Tactical Situation Area (TSA), according to the user's selection of QABs. The Auxiliary Readout area (ARO) is used to display Ownship data as well as all system messages.

In addition, DM also provides two pull-down menus. The first menu enables the user to set the range of distance represented by the TSA drawing area. The TSA menu allows the user to modify debug levels, select database functions and quit the system.

Should additional information be required for a particular target, the user can simply click the mouse in the TSA near that target. DM determines which track was selected by locating the closest MSDF track within a given tolerance of the user's click and then finding the associated CCS track, if it exists. This process is known as "hooking". The hook symbol is graphically represented in the TSA by a circle surrounding the target. Detailed information for both CCS and MSDF tracks is displayed in the CCRO area until the user releases the hook, or hooks a new target.

The previous *n* positions of a hooked track can be monitored by selecting the display track history QAB. Track history is represented graphically in the TSA by a series of *n* points.

1 UIM/X is a trademark of Visual Edge Software Ltd.

2 OSF/Motif is a trademark of Open Software Foundation, Inc.

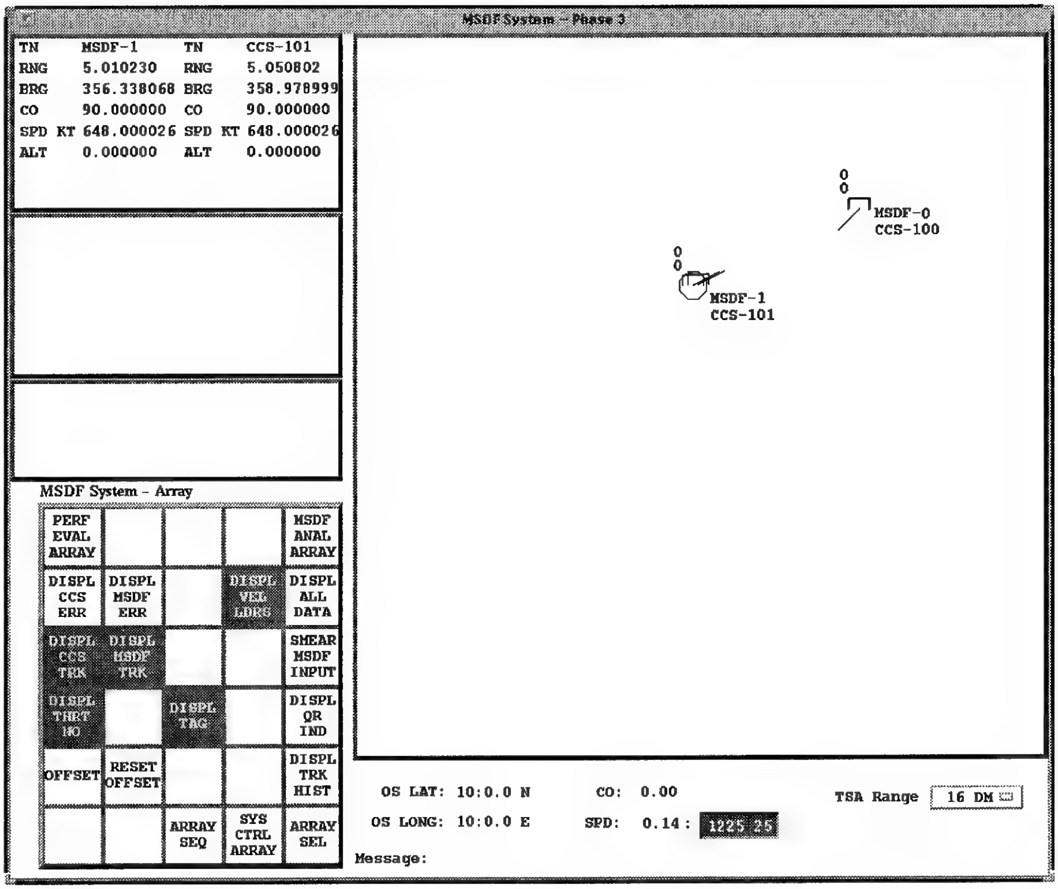

Figure 6. Man-machine interface snapshot of the MSDF System. Two tracks are shown graphically in the TSA with their respective track numbers is both CCS and MSDF systems. The track MSDF-1 has been hooked and the result of the hooking is shown in the CCRO at the upper left. The upper left numbers associated to each track in the TSA are the results of some tactical PE criteria.

The TSA area is centered upon the Ownship by default. The user can move the center point by selecting a QAB and pointing to the new center on the TSA. Another QAB resets the center of the display to the default value.

The modular design and flexibility of the DM module, and the MSDF system in general, enables rapid prototyping for future desired functionality, thereby keeping with the test-bed goal of the project.

5. CONCLUSIONS AND OUTLOOK

The design and implementation aspects of the MSDF demonstration model within the STDF real-time CCS have been discussed. While most of MSDF implementations in the open literature focus at finding optimal algorithms fusing data from various types of ideal sensors, this implementation selects fusion algorithms which are appropriate for the data available from the real sensors installed on CPF. We must deal with hard-decision sensors and tracks provided by the positional sensors (radars) which are incomplete (no covariance matrix). Since each sensor starts broadcasting information only for established tracks, it will not be possible to increase the target detection range by using sensor fusion. However the MSDF is still expected to enhance the CPF CS tracking and identification performance.

This project has taken the "shortest path" for this implementation, in that it has selected relatively simple, but more proven fusion algorithms. Only a subset of all the information available onboard the CPF platform is being used in these algorithms (the data from Participating Units (PU) through tactical data link systems, from the CIO sensor and the communications messaging data is not used). Although the first set of algorithms may not be optimal, since they represent a compromise, there are many benefits resulting from this implementation project, which include:

1. Establishment of a data fusion research facility, that will be used as a workbench by the team of scientists and engineers at UNISYS GSG Canada to understand the various data fusion implementation aspects within the current CPF and prepare for its proposed upgrade,
2. Analysis and selection of the MSDF algorithms appropriate for the type of data available from the CPF sensors,
3. Establishment of a capability to perform fusion of pre-recorded real sensor data collected during a trial, and compare the performance of the fusion algorithms with the performance of the CPF CCS,
4. Establishment of a modular system architecture within a UNIX environment that will support the real-time requirements of the MSDF system and can be spawned

into multiple processors, if the processor resource requirements increase to match the sophistication of MSDF algorithms,

5. Establishment of PE criteria that will quantitatively measure the performance gain as a result of incorporation of a MSDF capability within a platform's CCS.

The MSDF technology is opening a new dimension to the CS tactical performance analysis. Implementation programs, such as the MSDF demonstration model for CPF are essential for understanding this technology for establishment onboard the future platforms. With the MSDF workbench operational within the STDF, one can tackle several important future programs such as:

1. Fusion of all data available on CPF, including data from PUs, the CIO and messaging data,
2. Analysis of Wide Area Tactical Situation establishment using Joint Operational Tactical System (JOTS),
3. Analysis of sensor optimization and sensor queuing algorithms,
4. Analysis of Situation Assessment, Threat Evaluation, Weapon Engagement, and Cooperative Engagement algorithms.

6. ACKNOWLEDGMENTS

The authors wish to thank other Paramax R&D department data fusion scientists and engineers: Dr. M.A. Simard, C. Giasson, S. Jones and S. Charboneau who helped us with their comments. Other people at Unisys also helped: S. Bourassa, M. Doucet, S. Kamoun, Dr. R. Sassine and P. Fontaine. The DREV scientists L. Des Groseilliers and J. Roy supported the project with their technical contributions and discussions.

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ELECTRONIC COMBAT AND LETHAL DEFENSE SUPPRESSION

Leo J Rose
ASC OL/YHS, Bld 11
102 West D Ave, Suite 168
Eglin AFB, Fl 32542-6807

SUMMARY

Air forces across the world strive to protect their valuable resources from both the air and ground threats. Over the past few years, the surface-to-air missile threat has become more sophisticated and more deadly. It is far cheaper and less technical for a country to own and operate a ground missile system than to maintain a creditable air force. It is for this reason that the attention to the ground threat has grown over the past few years. This paper discusses the approach the US Air Force has taken in protecting its aircraft from these ground threats and how the mission of Lethal Defense Suppression has evolved into the complimentary tasks of Reactive Suppression and Pre-emptive Destruction.

TEXT

In times of shrinking budgets, force structure reductions, and undefined threats, the task of protecting friendly aircraft from ground threats has become more important. For the US Air Force, this tasks falls under the Operational Objective of Electronic Combat. As new advanced fighters become more and more costly, the loss of even one could amount to a political and fiscal price tag too high to pay. Potential adversaries have concluded that to develop, maintain, and train a credible air-to-air fighting force to protect their air space is far too expensive. A ground system, however, is much cheaper, easier to operate and maintain and as a result, the proliferation of Surface-to-Air Missile systems or SAMs has spread throughout the world. The role of Defense Suppression has become more important for the US Air Force as these threats grow in number and sophistication. To keep up with the improvements being made to the SAM's guidance and tracking, the Lethal Suppression of Enemy Air Defenses (SEAD), a subset of Electronic Combat, will undergo significant changes in the upcoming years, marking the end of one era and the beginning of another.

In the past, most modern air forces used a combination of tactics to improve the survivability of their aircraft, yet conducted the missions required to win the conflict. The US Air Force used the operational tactic of suppressing the regional threats just before and during the air strike. Although this method of suppression is somewhat successful, it is only a temporary disruption and must be repeated, thus requiring a great deal of resources throughout the campaign. In the next few years, a change of operational tactics will occur. This includes a shift of emphasis from suppressing SAMs to destroying them, from a dedicated SEAD aircraft like the F-4G Wild Weasel to a multi-role fighter performing several missions to include the SEAD mission, from a two seat to a single seat mission and finally from a unique missile (i.e. HARM) to a multi-purpose munition.

The US Air Force began this change of attitude during Desert Storm. During that conflict, the way we addressed the SAM threat seemed to be an inefficient use of air resources. For every strike mission, there was an accompanying escort of "HARM shooters" or Weasels tasked to provide protection from the surface-to-air threats. Even if the confidence level was high on the destruction of a particular SAM in a given region, the Weasel escort was still required. These assets could have been used more effectively escorting in other areas or performing different missions. This perception of inefficient use of resources needed to be proven analytically, however, and in 1992 the Air Force conducted a Mission Area Assessment and a Mission Need Analysis to document the worthiness of destroying SAMs in addition to just suppressing them. The Mission Area Assessment documents the operational objective and outlines the overall Concept of Operations. This assessment provides a basis for defining command-wide areas of emphasis and helps focus the Mission Need Analysis. The Mission Need Analysis assesses the capability to accomplish the Pre-emptive Destruction task, dealing with a defined set of conditions, such as force structure, threats, and environment, against a specified target set. Through this analysis, the force shortfalls and mission deficiencies that are identified are documented in a Mission Need Statement or MNS. During the simulation portion of the Mission Need Analysis, the scenario used was the Southwest Asia theater in the

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

year 2005. The enemy threats were allowed to operate in three levels of emission control: 1) completely netted together; 2) semi-autonomous; and 3) completely independent. The US Air Force force structure included F-15s, F-16s, EF-111 jammers, decoys to stimulate the threat, High Speed Anti-radiation Missiles or HARMs, HARM shooters (F-4Gs), and pre-emptive destruction weapons.

The model used to conduct the Mission Need Analysis was divided into two major methodologies: weapons level and campaign level. The weapons level model was TAC ARM, which was designed to produce HARM tactical probability of kill for a given threat or SAM. Inputs required include pre-launch and launch data for the HARM missile and the threat laydown of the SAM systems. The campaign level models consist of EADSIM - a raid level model, ESAMS - a SAM engineering model, and TAC EC - the campaign model. Together, these models produced several Measures of Effectiveness (MOEs). The MOEs include attrition of US Air Force aircraft, number of SAMs destroyed, and effects of each sortie.

The results of this study laid the foundation for the Mission Need Statement (MNS) for Lethal SEAD. The MNS documents the deficiency and discusses the operational aspect of the mission. Lethal SEAD mission objectives are broken down into two components, each complementing the other. The first is the immediate protection of friendly aircraft from SAMs. The second is long term air superiority achieved by the destruction of the SAMs. Further defined, the immediate protection of friendly forces is called Localized SEAD and is accomplished by reactive lethal suppression and non-lethal suppression or jamming. The air superiority mission is called Campaign SEAD and is accomplished by the pre-emptive and permanent destruction of an integrated air defense system.

The Lethal SEAD mission area is a sub-set of the Strategy-to-Task mission area breakdown. The top level mission of the Air Force is broken into three areas: support the ground forces, degrade the war sustaining capability, and attain air superiority. The strategy of Attaining Air Superiority contains four operational objectives, each of which contributes to the overall mission success. The MNS addresses only one of these, Countering Air Defenses. This objective is further broken down into the "task" of Destroying or Degrading the Air Defenses Lethally.

Expanding on this Strategy-to-Task concept, the Electronic Combat mission area is divided into four combat tasks: 1) Non-Lethal SEAD, 2) Command, Control, and Communication Countermeasures (C^3CM), 3) Electronic Warfare, and 4) Lethal SEAD. Non-Lethal SEAD consists of jamming the acquisition radars of the SAMs so as to confuse the operators and not allow them the ability to obtain a track solution. C^3CM involves jamming the communication links of the netted SAM systems as well as the "chain of command" link. Electronic Warfare is the self protection of the strike aircraft. The Lethal SEAD task deals with the degradation or destruction of the SAM system and is further divided, as mentioned earlier, into Reactive Suppression and Pre-emptive Destruction.

Reactive Suppression, as stated in the MNS, is the immediate protection of friendly aircraft. Because the strike package (i.e. friendly aircraft) is in the lethal area of the SAMs, the rapid detection, identification, and location of the threats is critical. The weapon launched must be fast enough to get to the target, in this case the SAM, before the target employs countermeasures. The fast missile does not imply that a "shoot out" exists between the Weasel aircraft and the SAM. Since the important feature in this mission is to protect the strike aircraft, destruction of the SAM is not required. As a result, assessing the damage inflicted upon the SAM is not part of the mission. Reactive Suppression starts with threat stimulation or causing the SAM's acquisition radar to turn on. The preferred way to accomplish this is by using some sort of decoy that acts like a strike aircraft. Without having decoys in the inventory, the next method would be to use the SEAD aircraft or Weasel acts as the excitor, playing a "cat and mouse" game with the SAM. The lest preferred stimulation is using the strike aircraft. Currently, the US Air Force uses the SEAD aircraft to accomplish the stimulation. The purpose of stimulation is to activate the SAM system in order to gather electronic order of battle (EOB) information. With this information, the SEAD aircraft can detect and identify the proper threat/target, then locate the target within some level of confidence. Once the target area has been evaluated, the SEAD aircraft will prioritize the targets and select the ones to encounter. The final step is to employ an anti-radiation missile (ARM) to suppress the SAM. The missile (i.e. HARM) must be fast enough to get to the SAM before it has a chance to employ countermeasures or shutdown.

Pre-emptive Destruction is the long term air superiority campaign designed to take out the SAMs for the duration of the conflict. In other words, the SAM (or threat) becomes the target and the mission is planned accordingly. Because strike aircraft (other than the SEAD aircraft) are

not in the area, time to detect, identify and locate the SAM is not critical. Since the terminal seeker will not rely on RF emissions a very fast missile is not required. In addition, the destruction of the SAM, as opposed to temporary disruption in the case of Reactive Suppression, is necessary to obtain the long term objective of air superiority. Finally, because the objective is to destroy the SAM, Battle Damage Assessment (BDA) or Bomb Impact Assessment (BIA) is also required. Pre-emptive Destruction requires the SAM to be stimulated in order to achieve Radio Frequency (RF) emissions. Because this mission is pre-emptive in nature (i.e. no strike package in the area) the method of gathering EOB data can be from either an off-board system or an on-board system, or a combination of the two. The target then must be identified, located, and prioritized. The final step of employing an ordinance must achieve a "hard kill" or permanently destroy the SAM.

After the Mission Need Statement was validated by the Chief of Staff of the Air Force, an Acquisition Decision Memorandum (ADM) was issued which began the development process of the program. This step is called a Milestone 0 decision in the US acquisition process. The ADM directed the implementing agency, Air Combat Command, in this case, to study the Pre-emptive Destruction mission, considering on-board and off-board targeting methods using Radio Frequency (RF) emissions as initial means of detection, location, and identification, and weapons capable of guiding on and destroying a non-emitting air defense unit. This study is called a Concept Exploration (CE). The CE is a top-down systems analysis that incorporates the targeting of the air defense unit, mid-course and terminal guidance of the weapon, and destruction of the target. The purpose of the CE is to identify alternate methods of accomplishing the Pre-emptive Destruction of SAMs. These results are passed to the Cost and Operational Effectiveness Analysis or COEA.

The COEA assesses the user's preferred alternative selections including cost of the system and technical risk. These selections are broad concept solutions, not specific designs. Those solutions that prove to be more cost effective are singled out and its characteristics are highlighted. The final selection is approved by the Chief of Staff of the Air Force and forms the basis for the Operational Requirements Document (ORD). The ORD identifies and documents the operational requirements necessary to meet the Mission Need Statement deficiencies. The ORD describes the system specific characteristics and related operational variables. It also defines thresholds and objectives of key parameters. These parameters form the basis for any follow-on demonstrations or development. The Concept Exploration and COEA combined form the Phase 0 activity in the acquisition process. The schedule for Phase 0 began Jan 94 and will continue through the end of FY95. The final product of the Phase 0 activity is an Operational Requirement Document (ORD) and will form the basis for the Statement of Work (SOW) for the Demonstration and Validation Phase, which will begin in FY96.

USING A RED TEAM TO DEVISE COUNTERMEASURES

R. L. Swedenburg, Colonel, USAF
Ballistic Missile Defense Organization/DSIM
Pentagon - 7100
Washington, D.C., 20301-7100, USA

SUMMARY

The ability of a defense system to operate effectively when deployed in battle is dependent on designs able to deal with countermeasures against the defense. The formation of a technical Red Team to stress the preliminary designs of the defensive system with technologically feasible and effective potential countermeasures provides a means to identify such potential countermeasures. This paper describes the experience of the U.S. Ballistic Missile Defense Organization's (BMDO) Theater Missile Defense Red Team since the Gulf War in 1991, the Red-Blue Exchange process, and the value it has provided to the designers of the U.S. Theater Missile Defense systems for developing robust systems. A wide-range of technologically feasible countermeasures has been devised, analyzed, tested for feasibility, and provided to the system developers for mitigation design. The process for independently analyzing possible susceptibilities of preliminary designs and exploiting the susceptibilities to identify possible countermeasures is explained. Designing and characterizing the Red Team's countermeasures, determining their feasibility, and analyzing their potential effectiveness against the defense are explained. A technique for the Blue Team's designers to deal with a wide range of potential countermeasures is explained.

1 INTRODUCTION

Many lessons have been learned from the Persian Gulf War when the Patriot missile defense system was first used to intercept tactical ballistic missiles. One lesson, evident from a perusal of the open literature of many countries, is that a nation intent on using ballistic missiles effectively in war will have to penetrate theater missile defense systems in the future. Another lesson widely learned by countries following the post-war analyses and the open discourse on Patriot Anti-Tactical Ballistic Missile effectiveness is that ballistic missiles can penetrate theater missile defense systems if the missiles execute adequate measures to counter the capabilities of the defense. Sometimes even inadvertent missile behavior, such as unexpected missile body breakups on reentry and the subsequent gyrating motion, can be an effective countermeasure to a defense system which was not designed to deal with such threat behavior.

Countries with an existing tactical ballistic missile arsenal intent on using them in the future, and countries currently building or buying tactical ballistic missiles for eventual use, and countries intent on selling their tactical ballistic missiles to other countries all have an interest in assuring their missiles do not become obsolete in the face of

Paper presented at the Mission Systems Panel 1st Symposium on "Guidance and Control for Future Air-Defence Systems" held in Copenhagen, Denmark from 17th May to 20th May 1994.

theater missile defense developments. It would appear that these countries have three choices: (1) accede to theater missile defense systems and deliver their warheads by means other than ballistic missiles, (2) acquire enough ballistic missiles to overwhelm missile defenses by sheer numbers, or (3) develop or otherwise acquire countermeasures for their ballistic missiles to penetrate the missile defense systems.

The U.S. Ballistic Missile Defense Organization began focusing on the above considerations shortly after the Gulf War. Beginning in May 1991, BMDO turned its Red Team, which was previously concentrated on strategic nuclear missile defense threat responses, toward the problem of addressing potential countermeasures to theater missile defense systems. The experience of its Red Team and the Red-Blue Exchange process was readily adapted to activities supporting the development of robust theater missile defense systems for the U.S.

Although Red Teaming is not a new technique, its most common usage by defense organizations has been in a war-gaming environment where existing military forces are pitted against each other. The technical Red Teaming conducted by BMDO addresses the preliminary designs of missile defense systems yet to be finalized -- not the wargaming of existing forces. This paper describes the utility of a Red Team for identifying potential adversary countermeasures to aid in designing robust missile defense systems. The paper is organized to describe the general need for a Red Team, the activities of the Red Team in the Red-Blue Exchange process, and the activities of the Blue Team in dealing with a wide range of potential countermeasures.

2 THE NEED FOR A RED TEAM

In order for a future defense system to achieve its operational requirements in battle it must be designed and built to operate effectively against enemy countermeasures. If the designer knows what countermeasures a future enemy will employ against his system, then he can design counter-countermeasures. The critical question is thus "What countermeasures will the enemy employ?" Most often,the answer is "We don't know." Most often, even the enemy doesn't know.

Countermeasures to a new defensive system are usually neither conceived nor developed by the enemy during the period when the new defense system is being developed. This is because the design is not finalized and the system is yet to be tested and produced. The enemy has very little knowledge of the defense system's operation or capabilities during the development phase, and adversaries are unlikely to devise and deploy counter-measures against something yet to be built. Consequently, there is little or no intelligence to be collected on enemy countermeasures. How, then, can the system engineer acquire an understanding of potential enemy countermeasures? BMDO's answer many years ago was to

form a Red Team to provide the enemy's perspective and to devise technologically feasible countermeasures to study and use for conducting counter-countermeasure design trade-offs.

The Red Team does not replace the intelligence collection activity, but rather supplements it. The Red Team provides an <u>advance warning</u> service to the system engineers designing the defense. In addition to providing this informal advance warning of potential countermeasures to the system developers, the Red Team's work in devising technologically feasible countermeasures is used by the formal threat development process, that is, the writing and validation of a document called the System Threat Assessment Report in the U.S. This report, which is an official document validated by the U.S. Defense Intelligence Agency, includes a description of deployed enemy countermeasures (when known), countermeasures under development by possible adversaries (when known), and countermeasures which are technologically feasible within the means of potential adversaries. Most often, however, we have no knowledge of countermeasures actually fielded, if any have been, nor of countermeasures under development, because of their secretive nature and the simple fact that potential enemies do not develop countermeasures against a defense system that is not yet built. This is why it is so important to have a Red Team devise <u>technologically feasible</u> countermeasures -- to presage the future enemy.

Since 1991, in the aftermath of the Persian Gulf War and the demise of the former Soviet Union, BMDO's Red Team has concentrated on understanding the perspectives of Third World adversaries and devising potential countermeasures to U.S. Theater Missile Defense systems under development. The Red Team operates within the structure of what are called Red-Blue Exchanges which will be described shortly. BMDO has performed three major Red-Blue Exchanges and found them extremely useful in uncovering potential countermeasures which need to be considered in the system design process. These Red-Blue Exchanges have been relatively inexpensive analytical activities and have provided a valuable service to the TMD system engineers. Technologically feasible countermeasures against the THAAD interceptor design, the Ground-Based Radar design, the Patriot ATBM Capability, the ERINT interceptor design, the CorpSAM interceptor design, and the Navy Aegis Combat System ATBM design have been devised and studied. The system engineers in these project offices now have potential threat countermeasure information to use for requirements development and counter-countermeasure design trade-off analyses.

<u>3. RED TEAM ACTIVITIES</u>

(U) To conduct a Red-Blue Exchange, BMDO convenes a Red Team of technical experts to simulate the adversary's perspective, a Blue Team of missile defense designers which includes the system engineers, and a Senior Review Panel of ballistic missile experts. The process is diagrammed in Figure 1. The

baseline threat scenario, the missile defense system architecture, and the ground rules are then agreed upon. The Red Team begins by analyzing the defense system and identifying susceptibilities which they think can be exploited by the enemy. They then devise countermeasures, characterize them operationally and technically, and provide them to the Blue Team. The Blue Team then analyzes the impact of the countermeasures on their designs, devises alternative responses, and provides counter-countermeasures back to the Red Team. The Senior Review Panel oversees this highly interactive process and judges the appropriateness of the Red Team's countermeasures as well as the Blue Team's responses. They also judge the effectiveness of the countermeasures and the responses against pre-established measures of effectiveness. The process usually takes several months culminating in a report which provides valuable information to the system designers as well as the threat developers.

The Red Team begins by collecting all the detailed technical characteristics of the Blue Teams's defense system. This includes, for example, the radar's parameters, the infrared missile seeker's characteristics, the interceptor's fly-out performance, guidance algorithms, warhead information, and the battle management rules and command and control protocols. The entire system is then modelled on a computer by the Red Team. Once it is modelled, the Red Team performs a susceptibility analysis to identify areas for countermeasure exploitation.

Specific countermeasures are then devised and combined into suites. The Red Team then performs an analysis to estimate the effectiveness of the countermeasure suites in degrading the defense, and estimates the degradation to the enemy's ballistic missile's performance due to adding the countermeasures. Typically, this is reduced range, reduced warhead mass, and possibly reduced accuracy. At this point the Red Team iterates, reviews its countermeasures, and makes adjustments to optimize the effectiveness of the suite. Convinced that they have devised the best countermeasure suite possible, the Red Team calculates the radar and infrared signatures, the mass, the volume, and other characteristics of the countermeasure suite design, and provides this package of data to the Blue Team for their response.

Before proceeding further to describe the Red Team's functions, it would be useful at this point to discuss the level of information on the technical characteristics of the Blue Team's system design which is made available to the Red Team. The degree to which the Red Team can devise a truly effective potential countermeasure is proportional to the amount of knowledge it has on the defense's technical design. If intimate details of the design are known, then it is usually easier to find susceptibilities and exploit them with specifically tailored countermeasures. This, of course, is why certain features of system

designs are protected through security classification. Now, although it is true that a potential enemy won't know everything about a system design, he may know anything. This conservative approach is the one usually taken in Red-Blue Exchanges in order to stress the design and to hedge against an adversary eventually learning the technical details of defense designs. It is best for the system developer to learn of any susceptibilities in his design before a potential adversary does. Then the developer can decide on how he wants to proceed in his design before committing it to test and production.

On the other hand it is useful to explore the effects which various levels of knowledge on the Blue defense system has on the ability of the Red Team to devise effective countermeasures. This can provide insight on which defense parameters are most critical with regard to enemy exploitation, and thus provide a requirement for protecting them to ensure they are not divulged. This is a unique spin-off of Red-Blue Exchanges. It is useful to vary the amount of information available to the Red Team in order to ascertain if any specific parameter, or combination of parameters, are especially useful to an enemy for exploitation. BMDO is doing this.

It was implied above that one of the many objectives of the Red Team is to stress all functions of the defense system's design. This is done to discover potential weaknesses before the design is committed to production. In order to stress the design adequately the Red Team must know all the details of each part of the defense system being studied. During the interactive play of the Red-Blue Exchange, the Red Team is tasked to prepare a chart that matrixes the defense functions across the top and the specific countermeasures devised by the Red Team down the side. The Senior Review Panel can then judge if all the defense functions have been stressed sufficiently by the Red Team's counter-measures.

The Red Team models the defense design under study using the amount of information on the design which is provided within the ground rules of the study. It uses the model as a primary tool throughout the Red-Blue Exchange, and its first use is to perform a complete susceptibility analysis. Figure 2 is an example of one of many curves generated in a typical susceptibility analysis. In this example, the Red Team determined how sensitive a specific interceptor's probability of kill would be to the acquisition range of its surveillance radar. The knee of the curve is obvious. If the Red Team can devise a technologically feasible countermeasure suite to reduce the radar's acquisition range to below the point indicated on the curve, then they will have a good countermeasure to stress the defense design.

The next step in this example is for the Red Team to devise

a specific countermeasure to exploit the steep slope of the curve in Figure 2. There are many possible ways to reduce the acquisition range of the sensor for a missile defense system. For example, an adversary could reduce the radar cross section of the warhead or reduce the infrared signature. He could mask the location of the missile or its warhead by using a radar jammer or infrared flares or aerosol clouds. The Red Team uses its knowledge of the defense system and its technical innovation to devise potential feasible counter-measures to exploit the susceptibilities and to overcome the capabilities of the defense system's design. The following two examples should help describe this process.

The first example will be called an <u>enveloping structure countermeasure</u>. This possible countermeasure could be devised in an attempt to preclude an <u>infrared</u> seeker on an interceptor in the <u>exoatmosphere</u> from locating the warhead in time to divert and intercept it. The Red Team would be stressing the end-game functions of the interceptor, specifically its sensor aimpoint selection capability and divert velocity. The enveloping structure would be deployed around the warhead after the warhead has separated from the booster beyond the atmosphere. The Red Team would invent the enveloping structure, choose its material, determine the weight penalty, and calculate its radar and infrared signatures. If the infrared signature of the warhead was sufficiently suppressed by the enveloping structure, it could be an effective countermeasure against infrared seekers in the exoatmosphere.

Another example is a <u>maneuvering threat warhead</u> to evade an interceptor in the lower portion of the atmosphere. The Red Team could devise a simple spiral maneuvering warhead using fixed position pitch and roll fins on the aft surface, for example. Such a modification to a warhead could be devised to stress the end-game functions of an <u>endoatmospheric</u> interceptor. If the spiraling warhead produced large enough accelerations without degrading its accuracy too much, the endoatmospheric interceptor may not be able to hit it, and the enemy could have an effective counter-measure.

The Red Team would model the endoatmospheric interceptor design and model the simple spiral maneuver to determine the change in single shot probability of kill as a function of altitude and cross-range. Battlespace and probability of kill within the battlespace could be the measures of effectiveness. After the Red Team determined the degradation in probability of kill, they may want to make changes to the design of the maneuvering warhead to optimize its performance.

<u>4. BLUE TEAM ACTIVITIES</u>

The Red Team <u>could</u> devise technologically feasible countermeasures, which can then be included in threat documentation, for use by the system developers <u>without</u> any interaction with the system

developers. BMDO, however, elected many years ago to use a Red-Blue Exchange process to provide a high degree of interaction between the Red Team and the Blue Team. The Red Team devises technologically feasible countermeasures and defends their credibility to the Blue Team. The Blue Team devises counter-countermeasure techniques for their designs and defends the restoration of the defense effectiveness to the Red Team. This back-and-forth technical play has proven to be a useful structure to achieve the following:

a) Ensure the system designers are made aware of design susceptibilities and potential countermeasures to their designs.

b) Ensure the system designers study countermeasure techniques for their designs and thoroughly analyze alternative responses

c) Ensure the system designers take a conscientious and informed decision on when and if the system design will be made to deal with technologically feasible countermeasures

d) Ensure a system is eventually fielded which can achieve its requirements even in a battle environment with unpredictable threat countermeasures.

The Red-Blue Exchange process is clearly an interaction where a great deal of learning and understanding on the nature of potential threat elements and the possible mpact on system design requirements takes place. For this reason, the Blue Team membership should include those project engineers responsible for establishing design requirements. One probable result of a Red-Blue Exchange would be modification or addition of technical requirements for the defense system. Another probable outcome would be changes to the functional allocation of technical requirements across the many components of the system design. In theory, the Blue Team leader would be the chief designer or principal system engineer in the system's project office.

Having introduced the need for a Blue Team, it is instructive now to discuss the two examples described earlier. These example countermeasures, the enveloping structure for the exoatmospheric phase of flight and the simple spiral maneuver for the endoatmospheric phase of flight, would be given to the Blue Team for their response in a Red-Blue Exchange. The data package would include the dimensions, weight, materials, operational concept, radar signatures in the proper band, infrared signatures, and six-degree-of-freedom trajectories. The data package on the countermeasures would be described and discussed at an interactive meeting, and the document delivered.

The Blue Team studies the data packages on all the countermeasures provided by the Red Team (which would be approved by the Senior Review Panel) and, as a first activity, questions the feasibility of the countermeasures. The Blue Team should muster all its engineering talent, take the role of a skeptic, and severely criticize the

technical credibility of each countermeasure. In this way, the Red Team is forced to defend the feasibility of their countermeasure designs, and everyone, including the Blue Team, acquires a much better understanding of the potential countermeasure.

Then, within the framework of their <u>response strategy</u>, the Blue Team devises both operational responses and technical design responses. Through innovation and expert knowledge the Blue Team of system designers looks for <u>alternative counter-counter-measures</u> to overcome the degradation caused by the Red Team's countermeasures. They must calculate the degradation caused by each countermeasure, devise responses, and then calculate the effectiveness of each response. Alternative counter-countermeasure responses must be evaluated. Trade-offs in design must be made. The impact of incorporating counter-countermeasures on the design, the cost, the schedule for acquisition and other programmatic impacts must be determined. The best response, or combination of responses, is then selected. Often, changes to operational procedures of the defense system can be found to mitigate the countermeasure, and these may be preferred over technical changes to the design. Having done all this, the Blue Team is ready to defend its responses to the Red Team.

In the examples of the enveloping structure and the simple spiral maneuver countermeasures, the Blue Team would devise both technical responses and operational responses. In the exoatmosphere against the enveloped warhead, the Blue Team could, for example, add a large diameter kill enhancement devise on the endo-exoatmospheric interceptor to strip away the tube with one shot and then follow-up with another shot to intercept the bare warhead. However, a less expensive response may be to simply let the atmosphere strip off the lightweight envelope, which would occur at a high altitude, and wait to intercept the warhead below this altitude. Even though the defended area footprint on the ground would be reduced if they wait to intercept, the resultant footprint may still meet the operational requirements of the system.

The Blue Team's response to the simple spiral maneuver could be, technically, to increase the interceptor's maneuver capability and guidance response by design changes. An operational response would be to intercept the warhead at a higher altitude where the atmosphere is not dense enough to cause significant maneuvers. This response could only be an option if the interceptor design has enough range.

One of the insights which may result from these examples is the utility of the high endo-atmospheric regime as <u>premium battlespace</u> against possible countermeasures. Lightweight countermeasures are stripped

away by the atmosphere at the higher altitude, and aerodynamic maneuvers are not significant above the lower altitude. This is depicted in Figure 3.

These examples are only two of a large number of technologically feasible countermeasures which a Red Team needs to analyze in the context of theater missile defense system designs. Of the many countermeasures which could be investigated in Red-Blue Exchanges, some will be more effective than others in degrading the performance of the defense system analyzed. This is to be expected. All the countermeasures analyzed by BMDO have been quantified regarding their <u>effectiveness</u>. Also, all the countermeasure concepts have been assessed with regard to the <u>difficulty</u> an adversary would have in designing, fabricating, integrating, and employing them in an operational environment. As expected, the difficulty of countermeasures for tactical ballistic missiles ranges from easy to hard. Quantifying the difficulty factor is itself difficult to do, and BMDO has embarked on a program to actually build and test selected potential countermeasures to better quantify the difficulty factor. This program involves the application of specific rules to constrain the countermeasures engineering team for the purpose of more closely simulating the technological capability of potential third world adversaries with ballistic missiles. The details of this program are beyond the scope of this paper.

The need to quantify both the effectiveness of potential countermeasures and the difficulty for adversaries to construct them is inherent in the methodology BMDO is applying as an aid for decisions on how best to address a large number of potential countermeasures. This methodology was devised by the TMD Red-Blue Senior Review Panel and it is depicted in Figure 4.

Referring to Figure 4, the <u>effectiveness</u> value of the countermeasure and the <u>difficulty</u> value of the countermeasure are plotted. Whether it's a radar jammer, chaff, an infrared flare design concept, decoys, intentionally tumbled boosters, or any other specific countermeasure concept, if it has been "played" in the Red-Blue Exchange then information exists to place the countermeasure on the effectiveness-difficulty plot. Due to the range of specific designs which are possible, "error bars" need to be added to the placement of each countermeasure.

Again referring to Figure 4, three regions (possibly more) can be constructed to aid the system engineer in deciding which potential countermeasures should be included in the system design requirements. If the countermeasure concept is not very effective in degrading the defense and also is quite difficulty to implement, then the system designer can probably dismiss the countermeasure. If, on the

other hand, the countermeasure would be very effective and also relatively easy to implement, then the design requirements should probably include the addressal of the countermeasure. The region in between these two is an area requiring tougher decisions. One way of dealing with countermeasures in this middle region is to estimate the "warning time" which intelligence collection activities might provide prior to the implementation of these countermeasures by an adversary, and then organize a separate upgrade project in order to be prepared for modifying the defense system when and if necessary.

Although this methodology for addressing a wide range of potential countermeasures in system design requirements is certainly not perfect, it does provide a reasonable starting point for making informed decisions concerning an area of great uncertainty. Designing counter-countermeasures against every conceivable countermeasure is unrealistic. This would be unaffordable within the budget of most defense systems, it would be excessive, and it would be unnecessary since adversaries would only implement a portion of all possible countermeasure concepts.

In conclusion, a notion expressed by the TMD Red-Blue Senior Review Panel chairman may be useful to relate. Missile defense system designers would prefer <u>clear evidence of the absence</u> of countermeasures in the threat they must address, but most likely they will receive <u>absence of clear evidence</u> due to the nature of countermeasures. It is this "absence of evidence" which dictates the need for a Red Team.

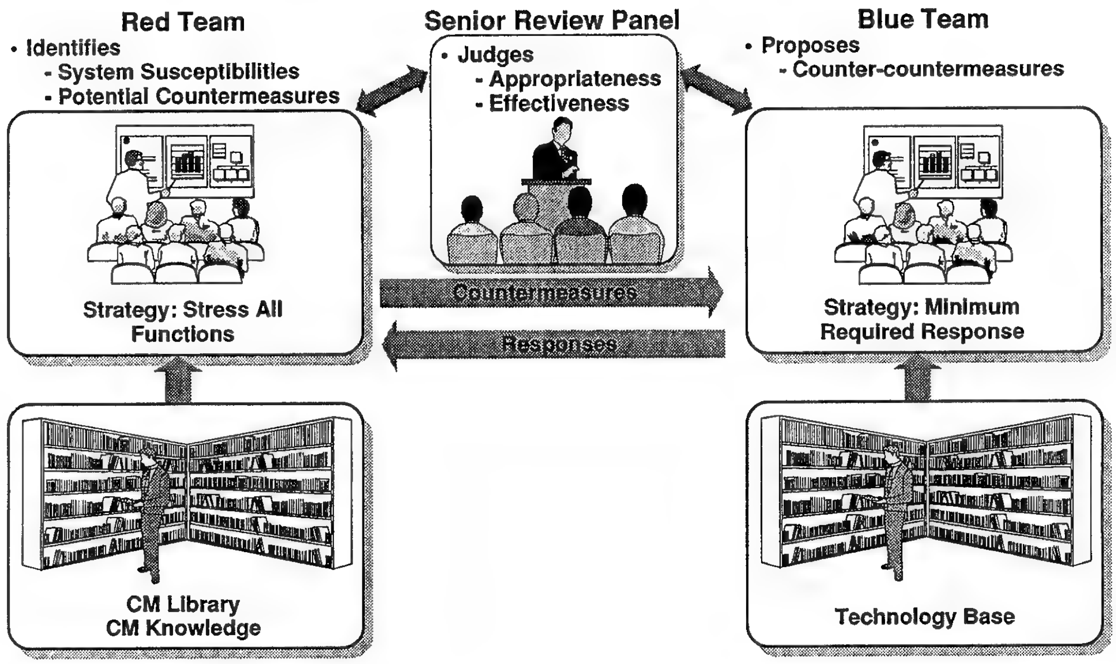

Figure 1. The Red-Blue Process

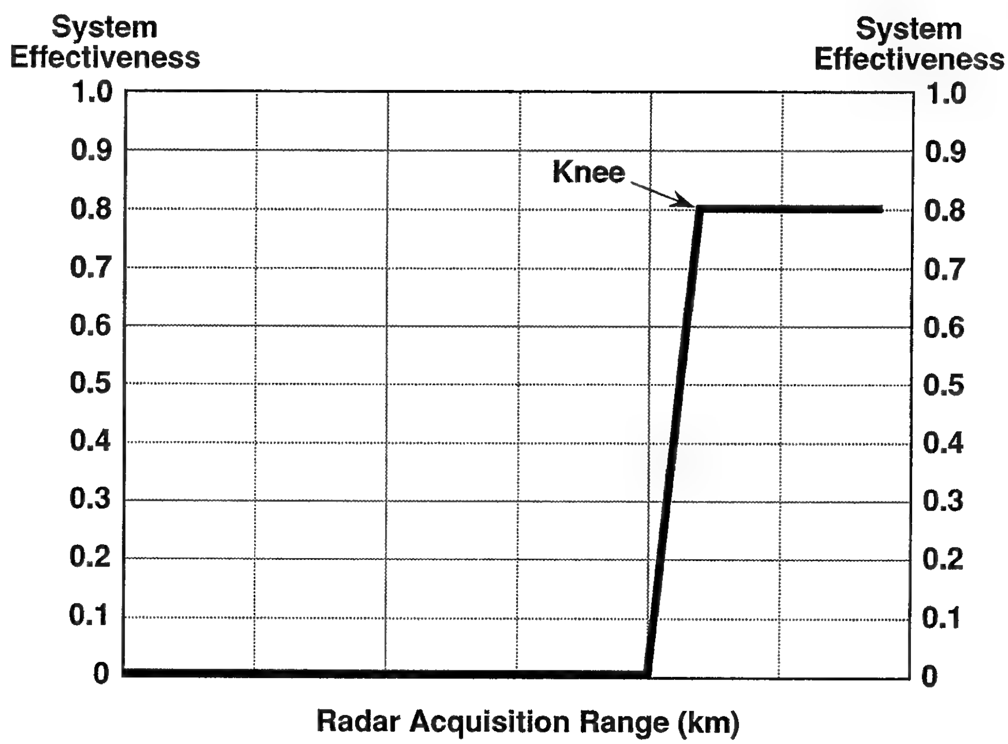

Figure 2. Example of Susceptibility Analysis

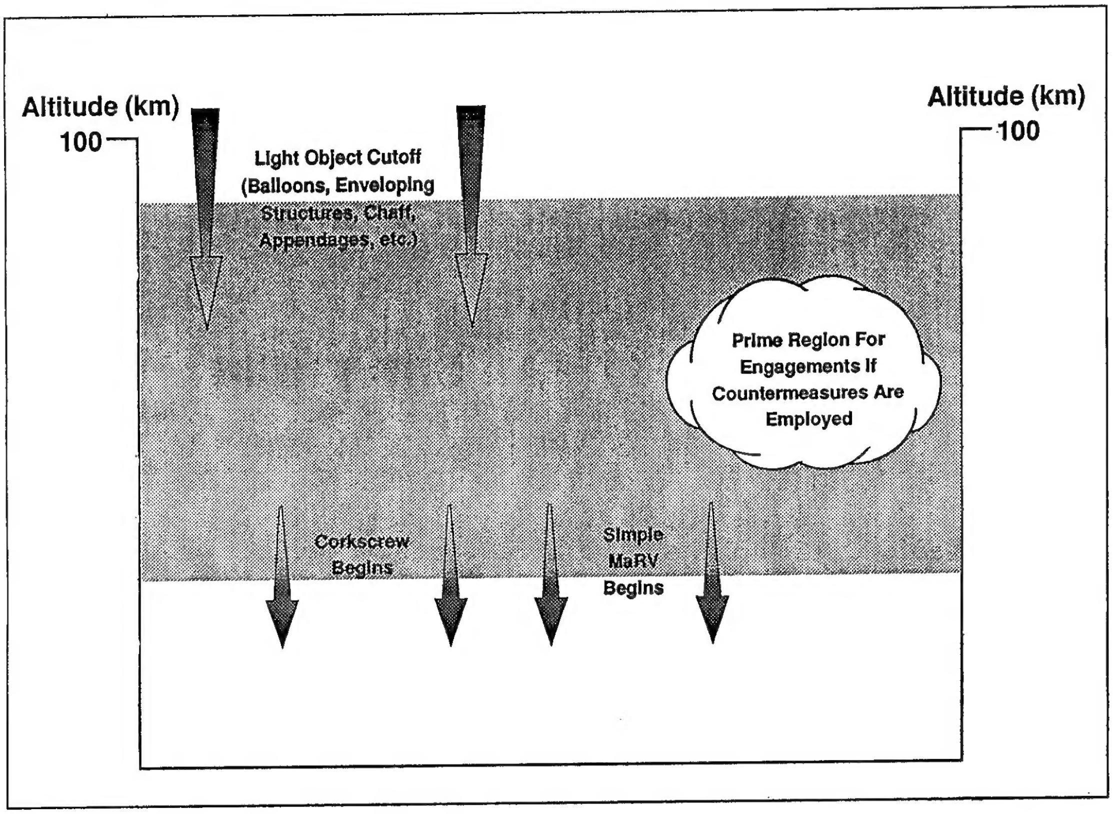

Figure 3. High Endoatmospheric Battle Space

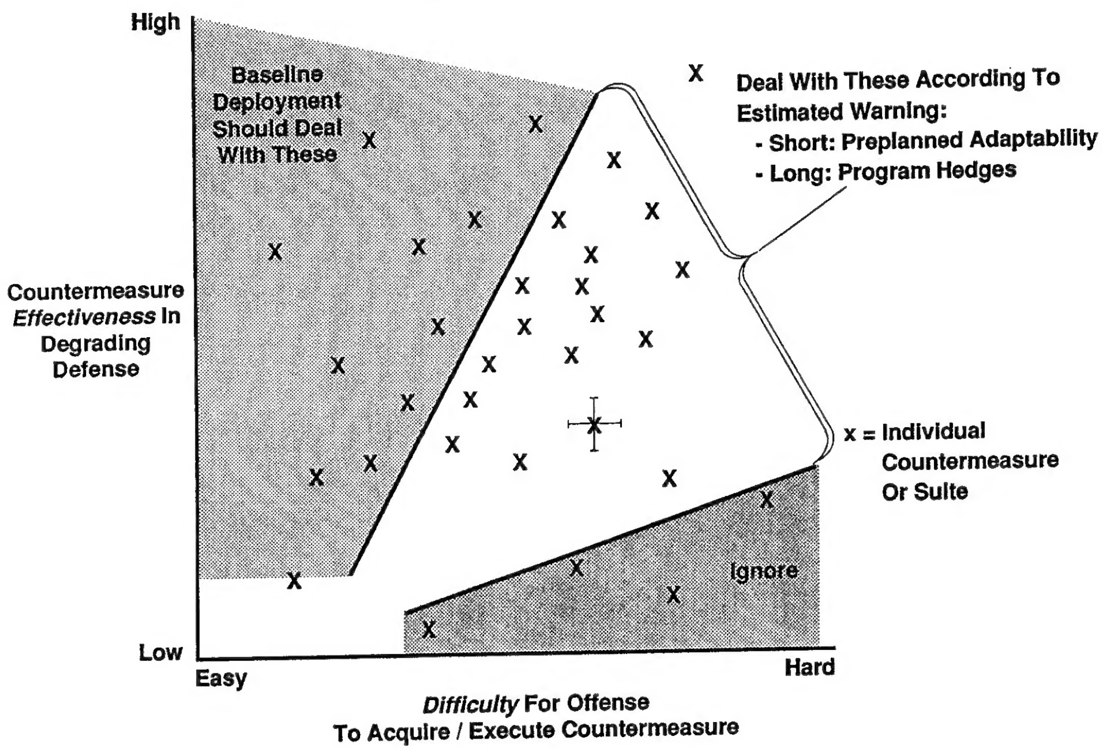

Figure 4. Dealing With A Wide Range Of Countermeasures

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-555	ISBN 92-836-0008-8	UNCLASSIFIED/ UNLIMITED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly-sur-Seine, France
6. Title	Guidance and Control Techniques for Future Air-Defence Systems (Techniques de guidage/pilotage pour les systèmes futurs de défense anti-aérienne)
7. Presented at	The Mission Systems Panel 1st Symposium held in Copenhagen, Denmark from 17th to 20th May 1994.

8. Author(s)/Editor(s)	9. Date
Multiple	January 1995
10. Author's/Editor's Address	**11. Pages**
Multiple	208

12. Distribution Statement	There are no restrictions on the distribution of this document. Information about the availability of this and other AGARD unclassified publications is given on the back cover.

13. Keywords/Descriptors

Air-defence	Data fusion
Ballistic missiles	Target acquisition
Guidance	Fire control
Control equipment	Defence systems
Integrated systems	

14. Abstract

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The papers presented covered the following headings:
- Ballistic Missile Defence Architecture and Air Defence Simulation;
- Advanced Sensors Technology and Techniques;
- Acquisition, Pointing, Fire Control and System Integration
- Data Fusion, Tracking and Identification;
- Threat Detection, Suppression and Situation Assessment;
- Missile Guidance and Control;
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